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Manned Spaceflight

The Society's interests cover a wide range. That is evident from the contents of the Society's publications and from the titles of the symposia we have been holding over the past few years (two of which—on Navigation and Liquid Hydrogen —are being published in this and the following issue of the *Journal*). However, our central interest is, and always has been, that of man's exploration and colonization of the Universe. Our interest in other subjects arises either because they are essential to the achievement of interplanetary flight (rocket propulsion is an obvious example), or because these subjects have certain aspects which touch upon astronautics.

We have always regarded the future achievement of interplanetary travel as something on a par with the emergence of the amphibia from the sea, a remove to an entirely new environment which would mark the beginning of a further stage in evolution. A significant step forward towards this achievement occurred this year, when Major Gagarin made the first orbital flight. This flight seemed a far more important development than the launching of the first Sputnik.

It was therefore with some surprise that we read recently a report that Mr. Denzil Freeth, Parliamentary Secretary to the Ministry of Science had said: "*We believe that our space programme is bringing far more in the way of scientific knowledge than by sending men or even dogs up into space. Sending people up is an expensive American and Russian hobby. The Americans and Russians are able to do it because the rockets were basically designed for defence purposes. They are sending gentlemen into space—and ladies too in time—as a by-product. According to our scientific advice, what they are getting for the money they are spending is quite frankly nothing like value.*"

Even if Mr. Freeth did not speak those very words, presumably he was in agreement with the general tenor of the report, for no denial or amendment was subsequently published.

As the Ministry of Science does not itself carry out space research, and does not appear to have any experts in astronautics on its staff, it seems likely that the advice which prompted Mr. Freeth's statement came from the University groups actively engaged in Britain's space programme. Now one would hardly expect these groups to advise the Minister that they were not giving him good value for the money he was spending but that is not the point. We accept that they give good value for the money they are allocated, such as it is. It may even be true that their work has yielded far more scientific knowledge than sending men or dogs up into space has done as yet, though that is less certain, for the scientific knowledge gained has been in different fields: physics on the one hand, physiology

and biology on the other. Furthermore, neither America nor Russia has disclosed just what information was gained in biological flight.

Our surprise concerns the remainder of the statement: that manned spaceflight is a hobby and a by-product. Mr. Freeth's use of the term "by-product" is unusual and not in accord with chemical practice, for he implies that a gentleman gets shot into space every time a missile is fired. But even accepting a looser usage, the statement is plainly untrue. Manned spaceflight is a major Russian objective, not a hobby, not a by-product. The Soviet space effort thus far can be interpreted as having been directed almost entirely towards the goal of placing man on the Moon; such scientific measurements as have been made are essentially part of that plan, although they may also be of interest in themselves.

The present American Mercury programme, and more advanced projects such as Dynasoar, also hardly merit being called a "hobby" just because they too are not likely to add much in the way of *scientific* knowledge. That is not the sole criterion for judging the worth of man's activities. We do not usually build aircraft only for the purpose of research in aerodynamics, or submarines just for studying the conditions near the sea bed, although there are some notable exceptions. The Minister for Science is responsible for the Department of Scientific and Industrial Research, a name which itself implies that *scientific* knowledge is not the only type of knowledge worth having or pursuing.

We expect to see a European space launcher organization in being before very long. Initially it will be concerned with the development of a satellite launcher based on an adaptation of Blue Streak as booster, but it must also concern itself with more advanced studies. We regard it as essential that manned spaceflight be included among these studies.

G. V. E. THOMPSON.

PROCEEDINGS OF THE SYMPOSIUM ON NAVIGATION AND THE EARLY EXPLORATION OF THE MOON

A symposium on navigation and the early exploration of the Moon, organized jointly by the British Interplanetary Society and the Institute of Navigation, was held in the Lecture Theatre of the Royal Geographical Society, 1 Kensington Gore, London, S.W.7., on Friday, 18 November, 1960. Ninety-four persons registered for the Symposium.

Details of the programme are given below and the papers and discussion are reproduced on pp. 131–158 of this issue of the *Journal*. Written communications and correspondence concerning the papers are invited, and should be sent to the Editor for publication.

Joint Organizing Committee

W/Cdr. E. W. Anderson (*Chairman*)

Mr. D. J. Cashmore
Mr. D. O. Fraser
Mr. S. W. Greenwood
Dr. N. H. Langton
Capt. A. M. A. Majendie
Mr. M. W. Richey
Mr. G. V. E. Thompson

PROGRAMME

Morning Session

Chairman: W/Cdr. E. W. Anderson (President, Institute of Navigation).

"The Demands of Nearly Parabolic Lunar Trajectories on Differential Correction and Perturbation Theory," by Professor Samuel Herrick (University of California, Los Angeles, and Aeronutronic Inc.).

"Guidance of Space Vehicles by Radio Measurements and Command," by A. R. Maxwell Noton (University of Nottingham).

Afternoon Session

Chairman: Dr. W. R. Maxwell (President, British Interplanetary Society).

"The Role of Inertial Equipment," by D. J. Cashmore (English Electric Aviation Ltd.).

"Surface Navigation on the Moon," by P. A. E. Stewart (Hawker Siddeley Aviation Ltd.).

General Discussion (*Chairman:* Air Marshall Sir Edward Chilton).

THE DEMANDS OF NEARLY PARABOLIC LUNAR TRAJECTORIES ON DIFFERENTIAL CORRECTION AND PERTURBATION THEORY*

By Professor SAMUEL HERRICK,† Fellow

ABSTRACT

The standard methods of orbit calculation employ different treatments for the ellipse, parabola and hyperbola, and cannot handle the rectilinear case. By choosing certain other parameters, rather than the usual elements of the orbit, the problem is greatly simplified and the resulting procedure is continuous through the elliptic, parabolic, hyperbolic and rectilinear orbits.

Successive measurements of position, even though affected by observational errors, will give a closer approximation to the true orbit. The basic formulae of the method are extended to the application of differential corrections and to the treatment of perturbations by mechanical integration, using either the methods of variation of rectangular coordinates or the variation of selected parameters.

It is regretted that the full text of this paper is not available.

* Paper presented at the Symposium on Navigation and the Early Exploration of the Moon, 18 November 1960, organized jointly by the British Interplanetary Society and the Institute of Navigation.

† University of California, Los Angeles, Calif., U.S.A.; also Principal Astrodynamicist, Aeronutronic Inc., a Divison of Ford Motor Co.

GUIDANCE OF SPACE VEHICLES BY RADIO MEASUREMENTS AND COMMAND*

By A. R. MAXWELL NOTON,† B.Sc., Ph.D., Fellow

ABSTRACT

The injection of space vehicles into orbit is dependent on guidance and control systems which are effective during the powered flight in the vicinity of the Earth. However, for most advanced lunar or interplanetary missions, the injection will not be sufficiently accurate and forms of post-injection guidance will be employed. This paper is concerned with such guidance and in particular with the important radio-command system which depends on ground radio-tracking, computing and command.

After summarizing the necessary ballistics theory, schemes of mechanization are discussed assuming the use of a small rocket (chemical propellent) mounted in the space vehicle.

The computation of the mid-course correction depends on the orbit determination, based on radio tracking of the vehicle by several sites located at widely dispersed points on the surface of the Earth. The method of orbit determination is explained and finally, for lunar and interplanetary missions, some examples are given in which the overall accuracy of such guidance systems has been calculated in terms of the various sources of error, *e.g.*, in pointing the rocket and determining the orbit from noisy radar data.

I. INTRODUCTION

The guidance employed during the early powered flight of a space vehicle is referred to as injection, boost or ascent guidance. The techniques are almost the same as those used in the guidance of ballistic missiles and they are not described in this paper. Instead, the correction of space trajectories by small impulse-type manœuvres is discussed, since injection guidance alone would not usually be sufficiently accurate for advanced space missions.

Such so-called midcourse manœuvres are applied by means of a small rocket motor mounted in the spacecraft. The magnitude and direction of the correcting impulse are computed on the ground from radio measurements and, prior to the manœuvre, the appropriate commands are sent by radio to the probe.‡ In addition to presenting the theoretical foundations this paper gives representative figures for the errors both in determining the orbit and in applying the correction. Reference is also made to tracking sites and the mechanization in the spacecraft.

II. THEORY OF MIDCOURSE MANŒUVRES

At this point it is convenient to assume that the actual trajectory followed by a vehicle differs only slightly from some precalculated standard trajectory. Linear perturbation theory may then be applied to all calculations dealing with coordinate variations and small velocity increments (for correcting the trajectory). Although for most purposes the approximations of linear perturbations are good, the theory is invoked more as a convenience than as a necessary step in the calculations. The theory is used to carry out first-order analyses but, where necessary, iterative procedures would refine the approximations.

If a probe reaches the desired destination point at a given time t_2 on the ideal or standard trajectory, then, because of injection errors, the probe will not, in general, reach the same point at time t_2 on an actual trajectory unless some correction is applied. Let the differences in the coordinates of position on the standard and the actual trajectory (in the absence of a correction) be $(\delta x, \delta y, \delta z)$ at time t_2. It is shown in Appendix A that, in order to correct the trajectory by applying a velocity-impulse with components (v_x, v_y, v_z) at some previous time t_1,

$$\begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix}_{t_2} = -H \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}_{t_1} \quad \ldots \quad (1)$$

where H is a (3×3) matrix, the elements of which can be determined from computations on the standard trajectory for any given t_1 and t_2. Components $(\delta x, \delta y, \delta z)$ at time t_2 can be computed indirectly from measured data and so the three velocity components necessary for the correction of the trajectory are determined by Equation (1). This would, however, guide the space probe to intercept a given moving point in space at a given time. The latter restriction would usually be unnecessary, small variations in the flight time would be permissible in most cases.

In order to allow variations of flight time, a new set of rectangular axes is taken (Fig. 1) centred at the probe position at time t_2 on the standard trajectory. The new axes are defined by the unit base vectors $\mathbf{e}_1$, $\mathbf{e}_2$, and $\mathbf{e}_3$, where $\mathbf{e}_3$ is along the probe velocity vector at time t_2 on the standard trajectory. Since $\mathbf{e}_2$ is in the xy-plane and perpendicular to $\mathbf{e}_3$ and $\mathbf{e}_1$, it completes the set of mutually perpendicular base vectors. If then $\delta\mathbf{R}$ is the vector displacement corresponding to $(\delta x, \delta y, \delta z)$ at time t_2 three new miss-components may be defined

$$M_1 = \mathbf{e}_1 \cdot \delta\mathbf{R}, \; M_2 = \mathbf{e}_2 \cdot \delta\mathbf{R}, \; M_3 = \mathbf{e}_3 \cdot \delta\mathbf{R} \quad \ldots \quad (2)$$

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* Paper presented at the Symposium on Navigation and the Early Exploration of the Moon, 18 November, 1960, organized jointly by the British Interplanetary Society and the Institute of Navigation.

† Electrical Engineering Department, University of Nottingham; formerly with NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena 3, California, U.S.A.

‡ The terms space vehicle, spacecraft and space probe are used synonymously.

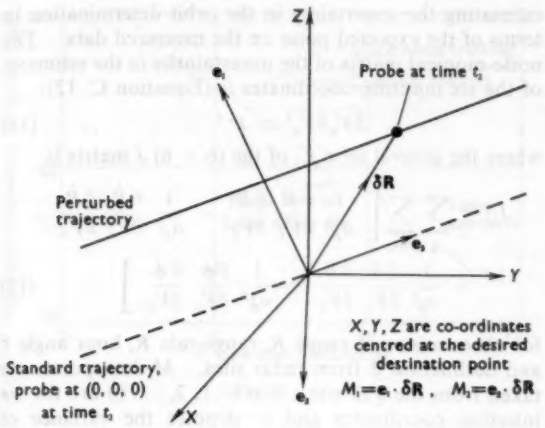

FIG. 1.

Assuming that, as a first-order approximation,* perturbed trajectories have the same velocity direction at time t_2, then M_1 and M_2 are the miss-components at some time different to t_2, and M_3 is associated only with time of flight variations. Thus

$$\begin{bmatrix} M_1 \\ M_2 \end{bmatrix} = \begin{bmatrix} l_1 m_1 n_1 \\ l_2 m_2 n_2 \end{bmatrix} \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix}_{t_2} \quad .. \quad (3)$$

where (l_1, m_1, n_1) and (l_2, m_2, n_2) are the direction cosines of $\mathbf{e}_1$ and $\mathbf{e}_2$, respectively. Indicating the (2×3) matrix of Equation (3) by N, Equation (1) can be modified to

$$\begin{bmatrix} M_1 \\ M_2 \end{bmatrix} = -NH \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}_{t_1} \quad .. \quad (4)$$

If the velocity components satisfy the above two equations, the trajectory would be corrected to pass through the desired end-point at some unspecified time. However, the three components have to satisfy only two equations, therefore there is one degree of redundancy, which may be used for one of the following:

(*a*) to minimize the magnitude of the correction;

(*b*) to apply a geometrical constraint to the manœuvre for the sake of practical convenience;

(*c*) to control an additional destination variable such as speed or time of arrival.

In the first case let

$$NH = [k_{ij}] \quad .. \quad .. \quad (5)$$

It can be shown that the magnitude of (v_x, v_y, v_z) is a minimum when

$$\begin{vmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ v_x & v_y & v_z \end{vmatrix} = 0 \quad .. \quad .. \quad (6)$$

Equation (6) defines a plane in which the correcting velocity vector would always be, when applied at a given time, t_1. The plane is independent of injection errors. The plane may be referred to as the most efficient or critical plane, the normal to that plane being the non-critical direction. The latter depends on the trajectory and the manœuvre-time along the trajectory. The non-critical direction is not always approximately parallel to the probe velocity vector.

In practice it may not be convenient to apply the correction in the critical plane. Referring to option (*b*) above, the correction might be restricted to a plane perpendicular to the probe-Sun axis. With a rocket mounted at right angles to that axis, one face of the spacecraft (carrying solar panels) need not then be turned away from the Sun during the midcourse manœuvre.

When the rocket thrust vector is restricted to a plane, critical or otherwise, the velocity components would satisfy an equation of the form

$$av_x + bv_y + cv_z = 0 \quad .. \quad .. \quad (7)$$

in addition to Equation (4). To calculate the velocity components, a (3×3) matrix is formed from the (2×3) matrix NH and a, b, c of Equation (7),

$$P = \begin{bmatrix} NH \\ \hline a\ b\ c \end{bmatrix} \quad .. \quad .. \quad .. \quad (8)$$

P being a (3×3) matrix. Then

$$\begin{bmatrix} M_1 \\ M_2 \\ 0 \end{bmatrix} = -P \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} \quad .. \quad (9)$$

and

$$\begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} = -P^{-1} \begin{bmatrix} M_1 \\ M_2 \\ 0 \end{bmatrix} \quad .. \quad (10)$$

which represents three equations specifying the velocity components (subject to a constraint) in terms of the miss-components M_1 and M_2. The latter would be obtained from the computed orbit according to the measured data.

Actually, in computing the necessary manœuvre during a flight, higher order terms would be taken into account. Equation (10) would be employed for each iteration in conjunction with exact integration of the equations of motion in a ground computer.

As regards the amount of manœuvring capability that a spacecraft must carry, this hinges on the accuracy of the injection guidance system, *i.e.*, how accurately the coordinates are controlled at burn-out of the last stage. The calculation of the magnitude of the manœuvre in terms of the statistical moment-matrix of injection errors is given in Appendix B.

* This approximation may be improved by taking out the effect of the attraction of the destination planet. Such a procedure is convenient for first-order error analyses.

III. ORBIT DETERMINATION FROM RADIO MEASUREMENTS

In order to compute the required midcourse manœuvre the trajectory or orbit of the space probe must be determined from Earth-based measurements. Such measurements would be from radar tracking and possibly photographic detection. Although the latter can be very accurate the processing time is inconveniently long, apart from the uncertainties due to weather. Radar tracking is therefore employed to provide the basic data for orbit determination.

Early spacecraft (*e.g.*, the U.S. *Pioneer IV* lunar probe) have carried only a radio beacon for tracking purposes, *i.e.*, a one-way link. In such cases only angular measurements are possible. Any Doppler measurements are dependent on the stability of the probe transmitter frequency and the velocity data become virtually useless. Later probes will carry a phase-coherent receiver and transmitter so that the probe transmitter frequency differs from the ground transmitter frequency only by the Doppler shift.* Accurate range-rate measurement is then possible. Range data can be obtained by a simple modulation of the carrier signal, but unfortunately such simple schemes require wide bandwith and consequently high power levels. More advanced modulation techniques are being developed for spacecraft in which long intervals of the carrier signal are modulated in a random fashion; for a given range accuracy the required bandwidth is then much less.

Tracking of space vehicles will be carried out at several sites in different countries but, in the U.S. space programme, heavy reliance will be placed on three sites which are being set up especially for the tracking of lunar and interplanetary probes. These are located at Goldstone in the Southern California desert, at Woomera (Australia) and possibly in the southern area of Africa. Each site will eventually have one 85-ft. diameter antenna for receiving and one for transmitting. Each site will therefore be able to send commands to the vehicle, apart from measuring the angular position, range-rate and ultimately the range of the space probe. In addition there will be communication links with the main computing centre in the United States, in order that the data can be processed and used for the in-flight orbit determination.

The central computer receives therefore many different kinds of measurements from different tracking sites. These measurements are contaminated by different kinds of noise. For example angular measurements are corrupted by refraction variations, antenna servo-jitter, slow mechanical deformations of the antenna, etc. Consequently the multitude of data points must be treated statistically (with the appropriate weighting) to determine the orbit which best fits the noisy data. The theoretical procedure is outlined in Appendix C. Apart from describing the method a result is also deduced for estimating the uncertainty in the orbit determination in terms of the expected noise on the measured data. The noise-moment matrix of the uncertainties in the estimates of the six injection coordinates is (Equation C. 12):

$$\overline{\delta V_u \delta V_u^T} = J^{-1} \quad .. \quad .. \quad (11)$$

where the general term j_{ij} of the (6×6) J matrix is

$$j_{ij} = \sum_q \sum_{m_q} \left[\frac{1}{\sigma_R^2} \frac{\partial R}{\partial V_i} \frac{\partial R}{\partial V_j} + \frac{1}{\sigma_{\dot{R}}^2} \frac{\partial \dot{R}}{\partial V_i} \frac{\partial \dot{R}}{\partial V_j} + \right.$$
$$\left. + \frac{1}{\sigma_\theta^2} \frac{\partial \theta}{\partial V_i} \frac{\partial \theta}{\partial V_j} + \frac{1}{\sigma_\phi^2} \frac{\partial \phi}{\partial V_i} \frac{\partial \phi}{\partial V_j} \right] \quad .. \quad (12)$$

for observations of range R, range-rate $\dot{R}$, hour angle θ and declination ϕ from radar sites. M data points are taken from the q'th site. $V_i (i = 1, 2, \ldots 6)$ are the six injection coordinates and σ^2 denotes the variance of noise on a particular kind of data (modified in the case of significant self-correlation).

Equations (11) and (12) are extremely useful for (*a*) predicting the precision of orbit determination for given radar sites, (*b*) specifying the required accuracy of radar tracking to determine orbits to a given accuracy and (*c*) evaluating the relative usefulness of different kinds of tracking. The results of some representative calculations are shown graphically in Fig. 2, which refers to a 76-hr. lunar trajectory injected over the South Atlantic Ocean.

A transformation has been applied to the moment matrix (Equation (11)) to express the results in terms of miss-components at the Moon. Thus, if W is the (2×6) matrix relating injection errors to miss-components, the dispersion of the miss-components M_1 and M_2 is given as

$$\begin{bmatrix} \overline{M_1^2} & \overline{M_1 M_2} \\ \overline{M_2 M_1} & \overline{M_2^2} \end{bmatrix} = W J^{-1} W^T \quad .. \quad (13)$$

Contours of constant probability in the $(M_1 M_2)$-plane are ellipses (assuming Gaussian noise on the measured data) and in Fig. 2 is plotted the semi major axis of the ellipse which contains 40% of all cases (loosely referred to as the *major miss-component*). If a perfect midcourse manœuvre were applied at any time T after injection, Fig. 2 shows the miss that would result at the Moon due to the uncertainties in the orbit determination.

Doppler measurements accurate to 1 m./sec. were assumed and such data are known to have an influence on the determination more powerful than the angular data. Fig. 3 is presented to demonstrate the value of range data from the tracking site at Goldstone, California.

One important conclusion from such studies is that the early tracking data have the strongest effect on the precision of the orbit calculation; if no radar tracking is available until about 5 hr. after injection then there is great difficulty in the numerical procedures and the orbit is known only approximately.

* The U.S. *Pioneer V* Space probe has such a system.

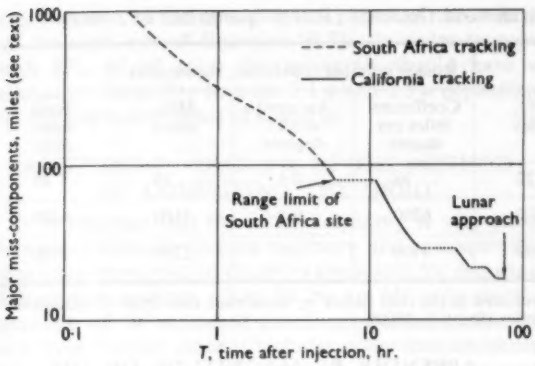

FIG. 2.

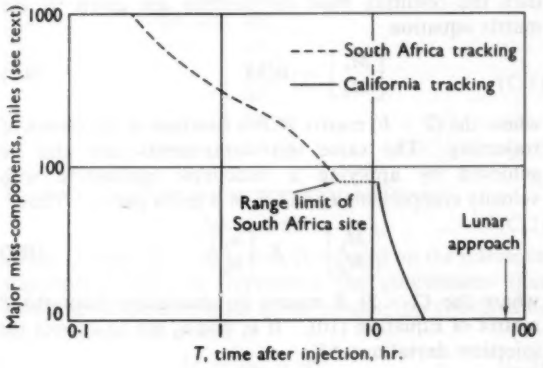

FIG. 3.

IV. MECHANIZATION AND SYSTEM PERFORMANCE

It was shown in Section II that a system of midcourse guidance includes a small rocket with a variable total impulse and the ability to point the thrust vector of the rocket in a desired direction.* Assuming that the rocket is mounted rigidly in the spacecraft, the angular orientation of the latter must be controlled and changed on command from the ground. Attitude control for lunar missions will be with a system of gas yets, but for longer interplanetary missions the addition of flywheel control will be desirable. Provided the electrical power comes from solar panels the weight of a flywheel system does not increase with journey-time.

The ease of shutting off and restarting liquid propellent rocket motors makes them attractive for midcourse manœuvres. Thrust levels can be quite low (*e.g.*, 50 lb.) and the lower specific impulses of monopropellents are acceptable in simplifying the propulsion unit. A separate tighter form of attitude stabilization would however be required during burning of the rocket. Shut-off of the motor would be dependent upon the integrated output of an accelerometer, mounted with the sensitive axis parallel to that of the thrust vector.

The choice of T, the time of application of the manœuvre is influenced by (*a*) the magnitude of the correction as a function of T, (*b*) the accuracy of the orbit determination as a function of T, and (*c*) visibility from tracking sites which can send the radio-commands. The calculation of the magnitude of the manœuvre is given in Appendix B but the result, as a function of T, is dependent on the relative values and cross correlations of the injection errors. This is illustrated in Fig. 4, where the midcourse manœuvre to correct one-at-a-time injection errors is plotted against T. It will be observed

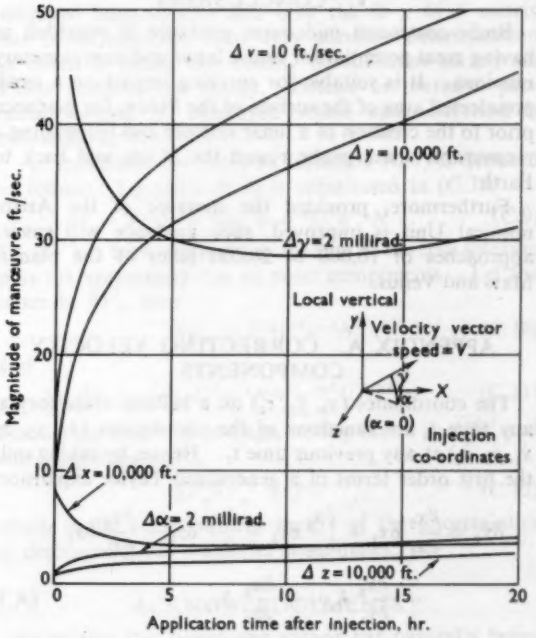

FIG. 4.

that they are *not* all monotonically increasing functions of T.

Taking into account considerations (*a*), (*b*) and (*c*) above, manœuvres in practice would typically be applied 10 to 20 hr. after injection on lunar missions and in the first few days of interplanetary journeys.

The accuracy of midcourse guidance depends on (1) the orbit determination, (2) shut-off of the rocket, and

* This is not, of course, the only possible mechanization. Another method is to make two manoeuvres in an invariant direction, although the first manoeuvre must be made very early to avoid using excessive amounts of rocket propellent. The orbit is not usually determined sufficiently only 2 hr. after injection.

TABLE I.—*Representative Figures for the Accuracy of Midcourse Guidance (R.M.S. quotations of errors)*

Destination	Orbit determination miss, miles	Rocket motor shut-off			Rocket pointing (100 ft./sec. manœuvre)			Total miss, miles
		Coefficient, miles per ft./sec.	Assumed error, ft./sec.	Miss, miles	Coefficient, miles per degree	Assumed error, degrees	Miss, miles	
Moon	40	22	1	22	38	0·5	19	49
Mars	4000*	3600	1	3600	6200	0·5	3100	6200
Venus	3000*	2500	1	2500	4400	0·5	2200	4500

* It is assumed that the uncertainty in the Astronomical Unit will be reduced in the near future by more than one order of magnitude[2]. Otherwise the miss at Mars and Venus would be the order of 15,000 miles (for 1 in 2000).

(3) pointing of the rocket thrust vector. Typical figures for these are summarized in Table I.

V. CONCLUSIONS

Radio-command midcourse guidance is regarded as having great potential for future lunar and interplanetary missions. It is suitable for ensuring impact on a small preselected area of the surface of the Moon, for guidance prior to the creation of a lunar satellite and for sending a recoverable space probe round the Moon and back to Earth.

Furthermore, provided the measure of the Astronomical Unit is improved, such guidance will ensure approaches of 10,000 to 20,000 miles of the planets Mars and Venus.

APPENDIX A. CORRECTING VELOCITY COMPONENTS

The coordinates (x_2, y_2, z_2) on a ballistic trajectory at any time t_2 are functions of the coordinates $(x_1, y_1, z_1, \dot{x}_1, \dot{y}_1, \dot{z}_1)$ at any previous time t_1. Hence, by taking only the first order terms of a generalized Taylor expansion,

$$\delta x_2 = \frac{\partial x_2}{\partial x_1}\delta x_1 + \frac{\partial x_2}{\partial y_1}\delta y_1 + \frac{\partial x_2}{\partial z_1}\delta z_1 + \frac{\partial x_2}{\partial \dot{x}_1}\delta \dot{x}_1 + \frac{\partial x_2}{\partial \dot{y}_1}\delta_1 \dot{y} + \frac{\partial x_2}{\partial \dot{z}_1}\delta \dot{z}_1 \quad .. \quad .. \quad \text{(A.1)}$$

and similarly for δy_2 and δz_2, where the perturbations are to be interpreted as coordinate variations from a standard trajectory. If, in addition to the six coordinate perturbations at time t_1, a further perturbation is added, an impulse of velocity with components (v_x, v_y, v_z) such that

$$\delta x_2 = -\frac{\partial x_2}{\partial \dot{x}_1} v_x - \frac{\partial x_2}{\partial \dot{y}_1} v_y - \frac{\partial x_2}{\partial \dot{z}_1} v_z \; .. \quad \text{(A.2)}$$

and similarly for δy_2 and δz_2. Then the net result will be that $\delta x_2 = \delta y_2 = \delta z_2 = 0$, since the applied velocity perturbation will exactly cancel the effects of the six coordinate variations at time t_1. Equation (1) is a statement of this result in matrix notation.

APPENDIX B. MAGNITUDE OF THE MANŒUVRE

Let δX be a (6×1) matrix of the six injection errors, then the resulting miss components are given by the matrix equation

$$\begin{bmatrix} M_1 \\ M_2 \end{bmatrix} = W\delta X \quad .. \quad .. \quad \text{(B.1)}$$

where the (2×6) matrix W is a function of the choice of trajectory. The same miss-components can also be achieved by applying a midcourse manœuvre with velocity components u_1 and u_2 in a given plane. Thus

$$\begin{bmatrix} M_1 \\ M_2 \end{bmatrix} = K \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad .. \quad .. \quad \text{(B.2)}$$

where the (2×2) K matrix is obtainable from the P matrix of Equation (10). If u_1 and u_2 are to correct the injection deviations δX,

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = -K^{-1} W\delta X \quad .. \quad \text{(B.3)}$$

and by multiplying each side of Equation (B.3) by its transpose

$$\begin{bmatrix} u_1^2 & u_1u_2 \\ u_2u_1 & u_2^2 \end{bmatrix} = K^{-1}W\delta X\delta X^T W^T K^{-1T} \; .. \quad .. \quad \text{(B.4)}$$

Let the six injection errors δX be now considered as random variables; the ensemble average of Equation (B.4) is

$$\begin{bmatrix} \overline{u_1^2} & \overline{u_1u_2} \\ \overline{u_2u_1} & \overline{u_2^2} \end{bmatrix} = K^{-1}W(\overline{\delta X\delta X^T})W^T K^{-1T} \quad .. \quad \text{(B.5)}$$

But $(\overline{\delta X\delta X^T}) = \Lambda$ is in fact the moment matrix of injection errors; it gives the variances and covariances of those errors and would be calculated from the form of the injection guidance system. Therefore

$$\begin{bmatrix} \overline{u_1^2} & \overline{u_1u_2} \\ \overline{u_2u_1} & \overline{u_2^2} \end{bmatrix} = K^{-1}W\Lambda W^T K^{-1T} \quad .. \quad .. \quad \text{(B.6)}$$

and the mean squared value of the midcourse manœuvre is

$$u^2 = \overline{u_1^2 + u_2^2} = \overline{u_1^2} + \overline{u_2^2} \quad .. \quad .. \quad \text{(B.7)}$$

i.e., the sum of the two diagonal terms of the matrix on the right side of Equation (B.7). In order to cope with 99% of all cases the spacecraft should have a manœuvre capability between 2·1 u and 2·5 u depending on the dispersion ellipse of u_1 and u_2.

APPENDIX C. OUTLINE OF THE METHOD OF COMPUTING THE ORBIT

It is assumed that the actual trajectory is very close to a pre-computed reference trajectory, and consequently, that linear perturbation theory is applicable for deducing first approximations. Let $\delta\psi$ be an $(M \times 1)$ matrix denoting all M measured coordinate perturbations; M is a large number since it includes many measurements of angles and range-rate (and possibly range) from several tracking sites. The trajectory can be completely specified by perturbations in the six injection coordinates

$$\delta V = \begin{bmatrix} \delta V_1 \\ \delta V_2 \\ \delta V_3 \\ \delta V_4 \\ \delta V_5 \\ \delta V_6 \end{bmatrix} \quad .. \quad .. \quad .. \quad \text{(C.1)}$$

Furthermore, from linear perturbation theory,

$$\delta\psi = U\delta V \quad .. \quad .. \quad \text{(C.2)}$$

where U is an $(M \times 6)$ matrix computed on the reference trajectory. Now $\delta\psi$ represents the coordinates that would be measured but for noise; actually, the coordinates $\delta\xi$ are observed, where

$$\delta\xi = \delta\psi + N \quad .. \quad .. \quad \text{(C.3)}$$

where

$$N = \begin{bmatrix} N_1 \\ N_2 \\ \vdots \\ \vdots \\ N_M \end{bmatrix} \quad .. \quad .. \quad .. \quad \text{(C.4)}$$

represents the noise components on all kinds of measurements at all times from all sites.

It is assumed that these noise components are associated with a multivariate Gaussian distribution, with the probability density function

$$P(N) = \frac{1}{\sqrt{(2\pi)^M |\kappa|}} \exp(-\tfrac{1}{2}N^T\kappa^{-1}N) \quad .. \quad \text{(C.4)}$$

where κ is the noise moment matrix of all M measurement-errors. By substituting Equation (C.3) in C.4)

$$P(N) = \frac{1}{\sqrt{(2\pi)^M |\kappa|}} \exp\left\{-\tfrac{1}{2}(\delta\xi - \delta\psi)^T\kappa^{-1}(\delta\xi - \delta\psi)\right\} \quad \text{(C.5)}$$

Computation of δV by the method of maximum likelihood[1] consists of maximizing $P(N)$ or, what amounts to the same thing, minimizing

$$(\delta\xi - \delta\psi)^T\kappa^{-1}(\delta\xi - \delta\psi) \quad .. \quad \text{(C.6)}$$

The solution for the (6×1) matrix δV, which minimizes expression (C.6), can be shown to be

$$\delta V = J^{-1}U^T\kappa^{-1}\delta\xi \quad .. \quad .. \quad \text{(C.7)}$$

where

$$J = U^T\kappa^{-1}U \quad .. \quad .. \quad \text{(C.8)}$$

However κ is an $(M \times M)$ matrix, where M may be as high as 1000; it would be impracticable to invert numerically such a high order matrix. Fortunately, it would usually be possible to assume that all the measurement errors are uncorrelated, in which case κ becomes simply a diagonal matrix of the variances of the noise on the different kinds of measurements at different times (in practice, if certain errors are self-correlated, it is sufficient to modify the variances in the diagonal κ matrix according to the correlation interval). The method of maximum likelihood then becomes the method of weighted least-squares and only the (6×6) J matrix has to be inverted. For very accurate determination of orbits it would not usually be sufficient to rely on linear perturbation theory. Instead an iterative procedure would be employed where each iteration is calculated as above.

An important corrolary to Equation (C.7) is deduced as follows: Equation (C.3) is substituted in (C.7):

$$\delta V = J^{-1}U^T\kappa^{-1}\delta\psi + J^{-1}U^T\kappa^{-1}N \quad .. \quad \text{(C.9)}$$

i.e., δV has been expressed as the sum of the true solution plus the uncertainty due to noise components. Let the latter be δV_u, then

$$\delta V_u = J^{-1}U^T\kappa^{-1}N \quad .. \quad .. \quad \text{(C.10)}$$

and

$$\delta V_u \delta V_u{}^T = J^{-1}U^T\kappa^{-1}NN^T\kappa^{-1T}UJ^{-1T} \quad .. \quad \text{(C.11)}$$

Taking the ensemble average, noting that $\kappa = \overline{NN^T}$ and using Equation (C.8),

$$\overline{\delta V_u \delta V_u{}^T} = J^{-1} \quad .. \quad .. \quad \text{(C.12)}$$

which is the noise-moment matrix of the uncertainties in determining the six initial coordinates.

ACKNOWLEDGEMENTS

In writing this paper, the author has naturally benefited from and made reference to the work of colleagues at the Jet Propulsion Laboratory. Specific acknowledgement is made to E. Cutting for his results on the accuracy of orbit determination and to F. L. Barnes for his work on midcourse manœuvres.

LIST OF SYMBOLS

H	matrix of differential coefficients.
J	(6×6) matrix of terms, j_{ij}, Eqn. (C.8).
K	matrix of differential coefficients.
K_{ij}	cofactor of k_{ij}.
M	number of measurements of all kinds.
M_1, M_2, M_3	miss components, Fig. 1.
N	matrix of direction cosines.
N	column matrix of noise components ($N_1, N_2 \ldots N_m$).

P matrix defined in Eqn. (18).
R observed range.
$\dot{R}$ observed range-rate.
δR vector displacement of $(\delta x, \delta y, \delta z)$.
U $(M \times 6)$ matrix of differential coefficients, Eqn. (C.2).
V_x, V_y, V_z velocity components of mid-course manœuvres.
δV column matrix of $(\delta V_1, \delta V_2, \ldots \delta V_6)$.
δV_u column matrix of uncertainties in the estimates of $(\delta V_1, \delta V_2, \ldots \delta V_6)$.
W (2×6) matrix relating perturbations at injection to miss-components.
δX column matrix of $(\delta x, \delta y, \ldots \delta \dot{z})$.
a, b, c constants.
$\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3$ unit base vectors.
j_{ij} element defined in Eqn. (12).
k_{ij} element of the K matrix.
l, m, n direction cosines.
m_q number denoting a particular measurement from the q'th site.
q number denoting a radar site.
t_1 time of midcourse manœuvre.
t_2 time at destination on standard trajectory.
u_1, u_2 velocity components of midcourse manœuvre in a given plane.
$\delta x, \delta y, \ldots \delta \dot{z}$ co-ordinate variations from standard trajectory.
Λ moment matrix of injection errors.
θ observed hour-angle.
κ noise moment matrix of all measurement errors.
$\delta \xi$ column matrix of observed perturbations in measured co-ordinates.
σ standard deviation or r.m.s. error.
ϕ observed declination.
$\delta \psi$ column matrix of computed perturbations in measured co-ordinates.

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DISCUSSION

Mr. E. E. Dweck commented on the application of the Principle of Contingency to the mathematical problems of space navigation, and to doppler navigation in particular.

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THE ROLE OF INERTIAL EQUIPMENT*

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(Communication from English Electric Aviation Ltd.)

ABSTRACT

A general survey of the navigation and guidance problems associated with flight between the Earth and the Moon is made, assuming that conventional high-thrust chemical rocket motors are employed. The approximate accuracy requirements for various types of missions are summarized and it is shown how the magnitude of the nominal initial velocity strongly affects these requirements, because of the close dependence of time of flight on this velocity. All but the more advanced and ambitious lunar missions require injection accuracies not exceeding those achieved with long-range ballistic missiles on Earth.

Three aspects of the problem which are not solved by present-day guidance of ballistic missiles are mid-course navigation, reliability and safety, and flexibility.

Ground-based radio systems could be used for mid-course guidance; alternatively, in the case of manned missions, optical observation from the vehicle of the Earth, Moon and, perhaps "beacons" placed at the equilateral positions of equilibrium would provide estimates of the vehicle's deviations from a pre-calculated trajectory. The velocity increment to correct the forecasted errors at the destination can then be computed by linear perturbation theory. The application of the velocity increment can be monitored by inertial equipment. For each particular mission, the balance between guidance accuracy and propellent required for mid-course corrections must be optimized.

The problem of reliability would become acute for lunar missions which last for days or weeks in an environment containing factors whose effects are not fully understood. To increase the overall safety of a manned mission, it would be desirable to back up ground-based radio systems by a combined optical-inertial system both for boost phase and mid-course guidance.

The flexibility of the self-contained guidance on the vehicle would be greatly enhanced by a lightweight digital computer which could be programmed to solve a variety of problems. By this means all the navigation and guidance equipment (including that for the terminal phases) could be integrated into a single system.

It is concluded that inertial equipment would be used during the boost phases of a lunar vehicle (in particular from the Moon on a return trip) and for monitoring mid-course correction manoeuvres, but that this equipment would be only part of single integrated system of navigation and guidance.

I. INTRODUCTION

In view of the rapid progress in space technology over the last three years, it is clear that human beings are on the verge of the exploration of the Moon. Indeed, this exploration has already begun. At the time of writing, one unmanned probe vehicle has circled the Moon and returned to the vicinity of the Earth, and another has impacted the Moon's surface.

It is therefore necessary to restrict any discussion of early lunar exploration to current capabilities in all the

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relevant technological fields. In particular, this paper presupposes that any vehicle used for lunar exploration is propelled by conventional chemical-fuel rocket motors. This has an important bearing on the navigation problem because low, continuous-thrust engines of the electrical type are thereby excluded at the outset.

Many people have pointed out that before manned lunar flight comes about, unmanned probes will be used to explore conditions in the Earth–Moon space and on the Moon itself. Even when manned flights become possible, it is very likely that preliminary sorties will come first. These would involve circumlunar trips, starting and finishing at the Earth, and the establishment of closed orbits round the Moon for close survey of the surface.

Needless to say, the navigation problems depend a great deal on the nature of the mission, particularly whether it is manned or unmanned. Any discussion of these problems must be closely related with specific missions. In what follows an attempt is made to forecast the role of inertial navigation equipment in various missions. The treatment is fairly general in the sense that detailed design problems are not closely studied, but nevertheless an attempt has been made to be realistic.

II. ORBITS

The nature of the orbit followed by a vehicle on a lunar mission will obviously have a strong bearing on the navigation problem. As indicated earlier, conventional chemical-propellent rockets are assumed. This means that a vehicle travelling between Earth and Moon will use its motors during a comparatively short boost phase at the beginning, coast freely for the greater part of the voyage and then use its motors again near its destination (or make use of aerodynamic forces in the case of arrival at the Earth).

Much has been published on the question of free-fall orbits in the Earth–Moon space and some references[1–18] are given at the end of this paper. This work falls into two distinct categories.

The first category uses a simplified model of the Earth–Moon system. This model is two-dimensional and assumes the Earth and the Moon to be rotating steadily in circular orbits about their common centre of gravity. The gravitational fields of the Earth and Moon are assumed to be due to point masses concentrated at their centres and the gravitational effects of the Sun and the other planets are ignored. The motion of a freely-falling vehicle of negligible mass is then found in terms of two separate two-body problems, namely Earth-vehicle in the vicinity of the Earth and Moon-vehicle in the vicinity of the Moon. The answers to this simplified problem can be found quite easily, but are, of course, only approximate and cannot be used to programme an actual flight. Nevertheless, they give considerable insight into the orbit parameters such as velocity, time of flight, etc., and are valuable in assessing the navigation and guidance problems.

In the second category fall the complete three-dimensional computations of specific trajectories. These computations demand the use of large-scale, general-purpose, digital computers. The complications that have to be dealt with include the Earth's axial rotation and its equatorial bulge, the ellipticity and orientation of the Moon's orbit and the gravitational field of the Sun. This computation is used for evaluation of actual lunar flight parameters and each computation gives the answer for a specific set of conditions, including the date and time of launch.

For the present purpose, only a broad picture of the orbits is required. A typical Earth-to-Moon trajectory with a total flight time of 58 hr. is shown in Fig. 1. The

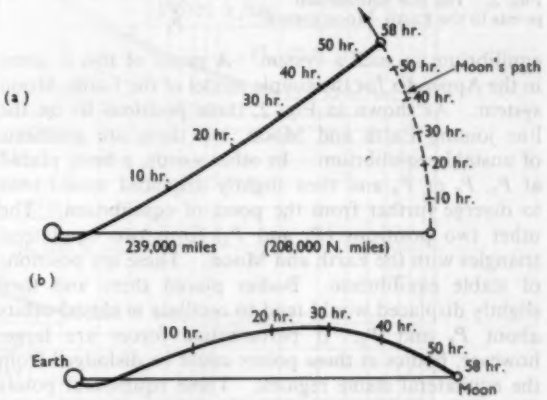

FIG. 1. Typical Earth-to-Moon trajectory.
(*a*) Relative to non-rotating frame.
(*b*) Relative to frame rotating with Moon.

rotation of the Moon round the Earth must be taken into account and the trajectory is illustrated in two ways. The first (Fig. 1*a*) shows the trajectory as seen from a non-rotating frame of reference. The second (Fig. 1*b*) illustrates how the trajectory will appear to an observer rotating with Moon round the Earth. The major part of the orbit can be seen from Fig. 1*a* to approximate to part of an elongated ellipse with focus at the Earth's centre. This is because the Earth is the predominating factor over most of the orbit, the mass of the Moon being only about one-eightieth of the mass of the Earth. In fact, the gravitational attraction of the Moon begins to exceed that of the Earth only after about 90% of the distance has been travelled.

Contrary to some popular expositions of the subject, however, there is no point on this typical trajectory where the vehicle could remain in equilibrium, that is, at rest with respect to the Earth and Moon. Even when the attractions of the Earth and Moon are equal in magnitude, they do not lie in opposite directions. Also the Earth–Moon system is rotating in space and, therefore, a body at rest in it must have some centripetal acceleration which must be taken into account. It can be proved that there are five distinct positions of relative

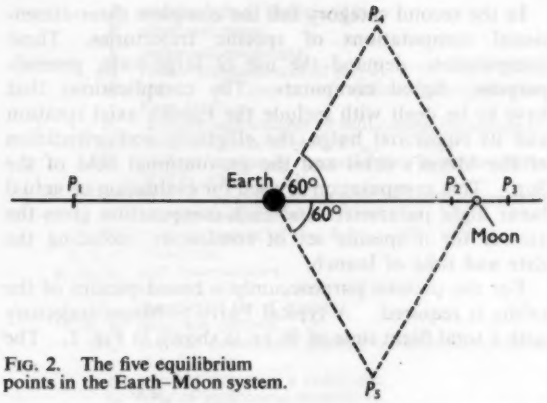

FIG. 2. The five equilibrium points in the Earth–Moon system.

equilibrium in such a system. A proof of this is given in the Appendix for the simple model of the Earth–Moon system. As shown in Fig. 2, three positions lie on the line joining Earth and Moon, but these are positions of unstable equilibrium. In other words, a body placed at P_1, P_2 or P_3 and then slightly displaced would tend to diverge further from the point of equilibrium. The other two positions (P_4 and P_5) form two equilateral triangles with the Earth and Moon. These are positions of stable equilibrium. Bodies placed there and then slightly displaced would tend to oscillate in closed orbits about P_4 and P_5. If perturbative forces are large, however, bodies at these points could be dislodged from the equilateral stable regions. These equilateral points P_4 and P_5 will later be referred to again.

Returning to the question of free-flight orbits between Earth and Moon, the flight times indicated in the typical

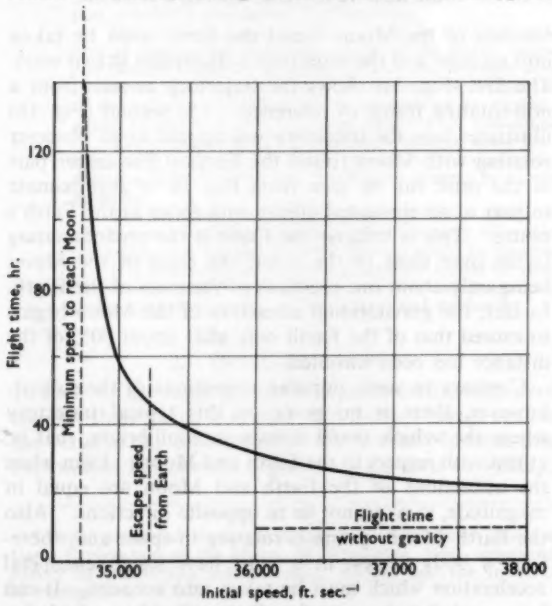

FIG. 3. Dependence of flight time on initial speed.

case of Fig. 1 is 58 hr. However, the flight time depends very much on the initial velocity of the vehicle and this is illustrated in Fig. 3. It will be appreciated that there is an infinite number of possible orbits between Earth and Moon, depending on initial position, velocity and direction of launch. To keep things simple, discussion on Earth-to-Moon orbits in this paper is limited to the case where the vehicle is injected into the coasting phase at an altitude of about 300 miles above the Earth's surface when the Moon still lies a little below the eastern horizon. Fig. 3 then shows how the flight time varies with the magnitude of the injection velocity, the direction being such as to make the vehicle impact on the Moon. It will be seen that the vehicle must have an initial speed of at least 34,800 ft. sec.$^{-1}$ in order to reach the Moon. For a speed just slightly in excess of this minimum, the vehicle takes 120 hr. to reach its destination. The 58-hr. case illustrated in Fig. 1 corresponds to a launch velocity of about 35,000 ft. sec.$^{-1}$. With a launch velocity of 36,000 ft. sec.$^{-1}$ (only 3·5% above the minimum) the flight time falls to 33 hr. As might be expected, as the initial velocity increases even further, the flight time tends towards the values it would have if no gravity existed. This high sensitivity of flight time to initial velocity has important repercussions on the question of accuracy and this is discussed in the next section.

III. ACCURACY

It is common practice to begin an assessment of a navigation and guidance problem by considering the accuracy requirements. This traditional approach is adopted here, although, as will be discussed later, there are possibly more important criteria to examine.

At this point it is essential to specify the missions under review. The missions considered for unmanned probes are:

(*i*) to impact on the Moon's surface;

(*ii*) to pass close to the Moon and swing back towards Earth in an unpowered orbit;

(*iii*) to use rocket motors in the terminal phase to establish a closed orbit round the Moon.

The same missions are included for manned vehicles. In addition, the return journey from Moon to Earth is considered for a manned vehicle for obvious reasons.

Fig. 4 shows the approximate accuracy of the magnitude and direction of the injection velocity required to achieve the stated accuracies for the various missions.

Since the Moon, and to some extent the Earth, is a moving target, errors in the time of flight will cause terminal errors. But it is shown by Fig. 3 that the nominal time of flight depends strongly on the initial velocity and, therefore, so do the terminal errors due to initial velocity errors. This is illustrated, for example, by the curve for Earth–Moon impact in Fig. 4. As the initial velocity on the nominal trajectory increases from 34,800 to 35,250 ft. sec.$^{-1}$, the required velocity accuracy relaxes from 5 to 200 ft. sec.$^{-1}$.

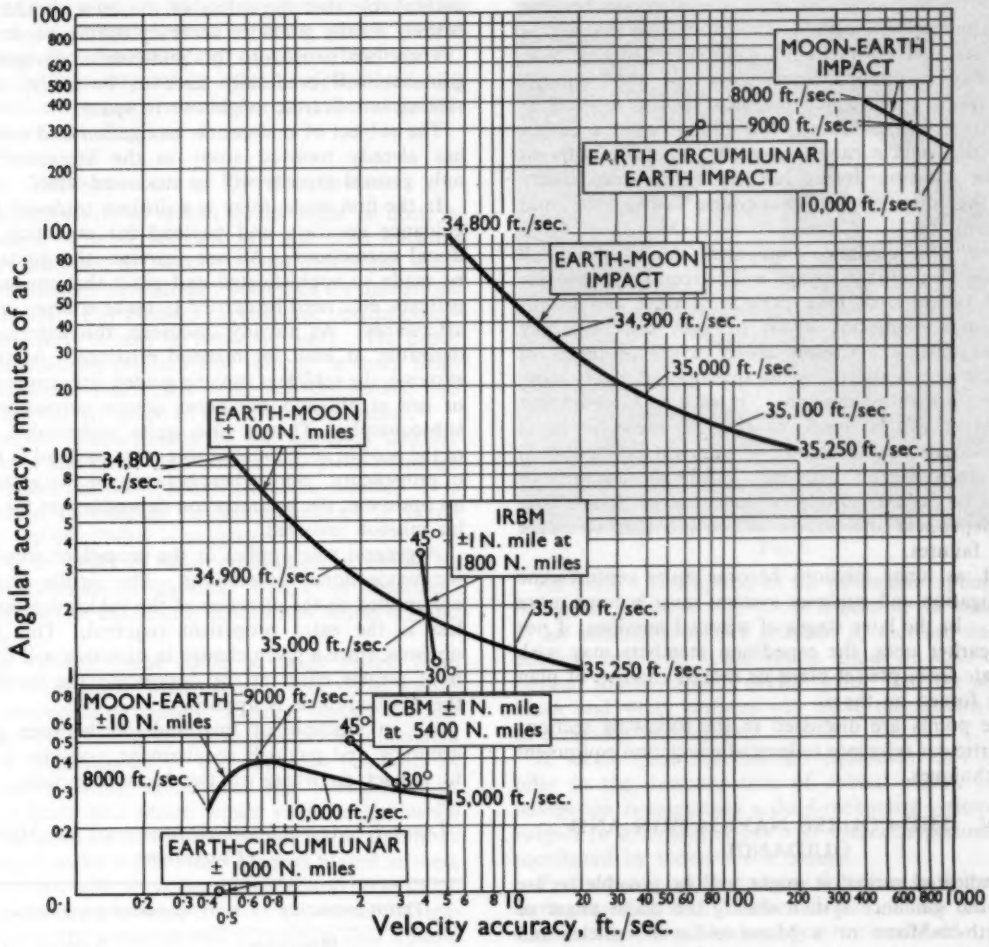

FIG. 4. Approximate accuracy requirements for various missions.

On the other hand, the error caused by a given directional error at launch becomes larger as the initial velocity is increased. Thus, at initial velocities near the minimum, an angular error is less important. The vehicle orbit still approximates to an ellipse tangential to the Moon's orbit, and the Moon simply overtakes the vehicle at a slightly different point and time. For example, to impact anywhere on the Moon with a launch velocity of 34,800 ft. sec.$^{-1}$ an angular error of 100 minutes of arc is allowable, whereas at 35,250 ft.sec.$^{-1}$ the angular accuracy must be tightened up to more like 10 minutes of arc.

The same general behaviour is reflected by all the accuracies for the various missions shown in Fig. 4. For comparison, the accuracies for Earth-bound ballistic missiles at two ranges are also shown in Fig. 4. These are based on Wheelon's paper,[19] and show the required accuracies at various launch angles from the horizontal. These points are useful since they indicate approximately the limit of present-day technology.

An important conclusion can be drawn from Fig. 4. With two exceptions, all the lunar missions specified require injection accuracies within the capabilities of the guidance systems of present-day missiles. Since the majority of ground-to-ground ballistic missiles use inertial guidance, it follows that inertial equipment could play a major role during the boost and injection phases of lunar vehicles. In fact, just as in ballistic missiles, a gyro-stabilized platform carrying accelerometers could steer the vehicle during boost and cut the propulsion when the velocity and direction required for injection have been attained.

It might be concluded from this that there are no new navigation problems in lunar exploration, but this would be wrong for three reasons.

In the first place, not every vehicle will be launched

with exactly the correct velocity and direction because of performance variations in the propulsion systems as well as residual errors in the guidance. In any case, present-day injection accuracies are not good enough for the more sophisticated missions such as arriving at the Earth from the Moon with ± 10 n. miles accuracy so that the vehicle can be steered aerodynamically to a specific location during re-entry. This immediately raises the question of mid-course navigation and corrections.

Second, the guidance equipment (and indeed all equipment) on a lunar voyage will be required to operate without failure over long periods of time and in environmental conditions which are only just beginning to be understood. Closely allied to the problems of reliability and longevity is the question of safety, particularly for manned missions. It must be assumed that every effort will be made to give the crews of lunar vehicles a reasonable chance of survival and eventual safe return to Earth. This may well imply that reliance will not be placed entirely on one type of system, but that independent alternatives will be provided to insure against failures.

Third, as lunar missions become more venturesome the navigation and guidance systems must become more flexible. In the later stages of manned missions, if not in the earlier ones, the expedition members may wish to deviate from pre-set plans or indeed changes of plan may be forced on them.

These points are discussed in the following sections with particular reference to inertial navigation equipment and techniques.

IV. MID-COURSE NAVIGATION AND GUIDANCE

As indicated earlier, it might well be possible to use an inertial guidance system during the boost phase of an Earth-to-Moon or a Moon-to-Earth vehicle, and thereby inject the vehicle into a free-fall orbit with acceptable errors. With present-day techniques, this would probably involve a platform stabilized by either three single-axis or two two-axis, low drift gyros. Three accelerometers mutually orthogonal would then provide measures of the components of vehicle acceleration in known directions and a navigation and guidance computer would integrate the acceleration data into velocity and displacement, and produce the appropriate steering and boost-cut signals. The accelerometers may themselves be singly or doubly integrating, thereby eliminating the need of one or two stages of computer integration. Such a system could be built to-day. It has the advantage of being entirely self-contained, but because of this demands a considerable amount of equipment.

Whatever form of boost guidance is used, there will always be residual injection errors due to guidance errors and propulsion variations. In the case of the more sophisticated lunar missions, these injection errors may not be acceptable, and for manned vehicles it is almost unthinkable that the safety of the crew should depend entirely on the guidance accuracy during boost.

Therefore provision for mid-course navigation and guidance will eventually have to be made, even for visiting our nearest neighbour in space.

The subject of mid-course navigation and corrections has already received study in the literature[11,30] and only general aspects will be discussed here.

In the first place, there is a distinct trade-off between guidance accuracy and payload for executing navigational corrections. At one extreme, the guidance can be made so sophisticated and exact that no extra propellents, etc., need be carried to make course corrections afterwards. As already discussed, this extreme is undesirable, at least for manned missions. At the other extreme, the vehicle is initially guided only approximately or not at all, and numerous course corrections made subsequently. This is also quite undesirable because of the need of very considerable extra payload in the form of propellents. Somewhere between the two extremes lies an optimum, the optimization depending on the particular mission involved.

A general rule applies to the propellent requirements for navigational corrections. The *earlier* corrections are applied to the *direction* of the vehicle trajectory, the less is the extra propellent required. This is fairly obvious, since a given change in direction will in general have greater effect at the destination the further from the destination it is applied.

As an example of this trade-off between guidance accuracy and payload requirement, consider a mission to impact anywhere on the Moon's surface. Table I

TABLE I.—*Approximate Requirements for Mid-Course Corrections*

Thrust correction		Guidance accuracy required		
Made at	Magnitude, ft. sec.$^{-1}$	At	Velocity, ft. sec.$^{-1}$	Direction, degrees
Cut-off ..	—	Cut-off	± 40	$\pm 0{\cdot}3$
Mid-Course (75,000 n. miles)	460	Cut-off Mid-Course	± 100 ± 44	± 1 $\pm 0{\cdot}5$
Cross-over (215,000 n. miles)	2500	Cut-off Cross-over	± 100 ± 260	± 1 ± 6

(which is based on Brown and Fleisig[13]) shows the magnitude of the velocity correction and the guidance accuracies required for three cases:

(*i*) no navigational corrections;

(*ii*) correction made after 75,000 n. miles (called the "mid-course" point);

(*iii*) correction made after 215,000 n. miles (near the "cross-over" point between gravitational fields of Earth and Moon).

Whenever they occur, mid-course manœuvres can be considered to comprise three distinct phases. First must come the determination of the orbital errors, secondly the necessary action must be determined and thirdly the correction manœuvre must be executed. These phases are discussed in turn.

1. Determination of Orbital Errors

The determination of orbital errors might be done in various ways. The methods of radio and radar tracking have been discussed by Noton[21,22] and others and some of these techniques have already been used for unmanned probe vehicles. For manned expeditions, optical observations are likely to play an important part. The problem of determining position and velocity in space from astronomical observations is being actively studied and some references are given at the end of this paper.[23–32] For example, measurements of the apparent angular diameters of the Earth and Moon will yield estimates of the distances of those bodies from the vehicle. It is not intended to examine optical techniques in detail here, but one possibility is suggested.

In the later stages of lunar exploration, it should be feasible to establish navigational "buoys" or "beacons" at each of the two equilateral equilibrium points (P_4 and P_5 of Fig. 2).

If large enough, these could be made visible from anywhere in the Earth–Moon space. For visual identification, they could be coded in alternate black and white areas and set rotating so as to present a modulated intensity. Observations of the apparent positions of these beacons, either against the star background or relative to Earth and Moon would yield further useful data on the position of the vehicle. A more ambitious system might make use of radio beacons placed at these points—for example, a system of master and slave transmitters could provide some form of hyperbolic navigation. It is worth noting in this connection that a radio beacon on the Moon's surface would appear roughly stationary in the triangulation system, except for the Moon's libration and orbital eccentricity. The libration would cause the equilateral points P_4 and P_5 to appear to move in approximately a circle of radius subtending 7° as viewed from a fixed point on the Moon. Owing to the ellipticity of the Moon's orbit, the distances between the Moon and the equilateral points would vary cyclically. These variations could perhaps be allowed for by slow continual phase or timing changes in the transmissions, since the variations would only be slow, one cycle taking one month. It will be realized that a system comprising, say, a master station on the Moon and slave stations at the two equilateral points will not provide a complete fix. The phase or time comparison of signals received from these stations would only fix the vehicle position somewhere on the intersection of two hyperbolic sheets, but these data together with data from other sources (*e.g.*, visual measurements of angular diameters of Earth and Moon) could be valuable.

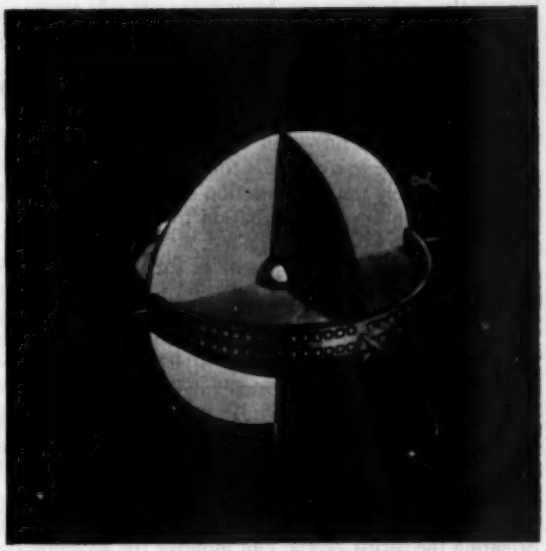

Fig. 5

An artist's conception of an automatic optical/radio beacon is shown in Fig. 5. It is built in the basic form of an octahedral corner reflector to increase its radar-echoing area. It would rotate about an axis roughly normal to the Moon's orbital plane, and the alternate black and white surfaces will make the beacon appear as a rapidly varying star.

It seems clear that inertial equipment has little to offer in the determination of orbital errors. Inertial navigation is essentially a dead-reckoning system and is subject to diverging errors over extended periods if not monitored by independent means.

Furthermore, accelerometers will necessarily read zero during free-fall, and therefore do not indicate the vehicle acceleration due to the local gravitational field. In fact, it would perhaps be wise to disconnect the accelerometers from the dead-reckoning computer to avoid bias errors integrating up into unacceptable velocity and position errors. However, it is quite possible that the dead-reckoning computer, with computed compensation for gravity, could be in continuous operation and brought up to date as fixes are taken by other methods (see Section VI).

2. Computation of Correction Manœuvre

It is likely that for every mission between Earth and Moon, a nominal trajectory will be pre-computed which the vehicle would ideally follow. In practice, however, the vehicle will deviate from this ideal trajectory. It is then possible to describe the vehicle position and velocity in terms of deviation or perturbations from the nominal values at each instant. As described by Lawden[33] and Noton,[21,22] the manœuvre (*i.e.*, velocity change) required to cancel the effects of these deviations at the destination can then be computed by linear perturbation theory,

provided the deviations are not too large. Once the values of the deviations have been determined, the required velocity change can therefore be computed, either on board the vehicle if navigation is self-contained or at a ground base in the case of remote control.

If this linear perturbation technique is employed, it perhaps gives rise to a criterion for the injection guidance accuracy, namely that the injection errors are kept small enough for the linear perturbation theory to have adequate accuracy when it is applied.

Clearly, no inertial equipment as such is involved in this phase, but the associated navigation computer might well be called upon to carry out the necessary calculations (see Section VI).

3. Execution of Correction Manœuvre

Motor thrust must be applied to produce the required velocity change. This thrust is required to act in a certain direction and to produce a certain magnitude of velocity. It is here that inertial equipment is particularly suited, for it can provide a directional reference for orienting the thrust vector, can monitor the acceleration applied and terminate the thrust when the desired velocity increment has been achieved.

In free fall, gyro drifts due to unbalanced mass will not occur, but gyros will still drift as a result of flex lead torques, pick-off reaction torques, etc. An unmonitored gyro-stabilized platform can therefore not be expected to maintain its orientation with high accuracy over long periods. Some form of external direction reference must therefore be envisaged, such as star-tracking telescopes or sun-seekers. Under these conditions, the telescopes or sun-seekers provide the basic long-term direction reference and the gyros act as short-term "memories" during occultation of the telescopes, etc.

Angle pick-offs on the platform gymbal system then give the data necessary to orient the thrust axis in the required direction.

Accelerometers on the platform could then monitor the application of thrust. It is to be noted that a single accelerometer rigidly aligned along the thrust axis would be sufficient for this particular purpose. However, if platform-mounted accelerometers are used during boost guidance, these can also perform this function. Table I shows that for a simple lunar impact mission, only about 10% accuracy is needed for the velocity increment, which is easy to achieve. For more ambitious missions, the required accuracy would be higher, but should be within the capability of inertial equipment.

V. RELIABILITY AND SAFETY

The initial assessment of the navigational problems was couched in terms of accuracy. This is obviously an important criterion, but when it comes to the question of instrumentation the problem of reliability must seriously be considered at an early stage in design. It is unthinkable that a manned lunar vehicle should use unproved equipment for navigation or indeed for any other purpose. Reliability has been much discussed in recent years, particularly in relation to aircraft and missiles, and the lessons learned in these fields must be applied to lunar exploration.

To increase the overall safety factor for an expedition, it may well be desirable to provide various independent navigation and guidance means. Ground-based radio and radar systems could no doubt play an important part, but for a manned expedition it would be very desirable to provide self-contained systems in addition. If the ground equipment breaks down or communication with it is lost, then the crew would still be capable of finding their way about. From this point of view, a combination of optical fixes and inertial dead-reckoning is attractive. Furthermore, while ground-based systems are operating satisfactorily, the radio, optical and inertial data could be combined to give increased accuracy.

A considerable amount of effort over the last decade has gone into improving the reliability and longevity of inertial equipment, and it is natural to enquire whether a stage has been reached where such equipment could be operated satisfactorily on lunar missions. It is not proposed to give a definite answer to this question here, but only to survey briefly some of the factors involved. Definite answers can only be given after a good deal more experiment and experience.

It has been indicated in this paper that gyros and accelerometers would only be operated during the boost phase and during mid-course corrections. From this point of view, therefore, the equipment is not required to operate continuously, but it must be possible to switch the equipment on and off several times without failure. On the other hand, the navigation computer may well be asked to operate continuously as a dead-reckoning device (see Section VI) during a whole trajectory.

Equipment operating on a lunar expedition will have to operate in environmental conditions whose effects are not yet fully understood. These environmental factors include weightlessness, high vacuum, meteorites, meteoric dust, cosmic rays, X-rays, ultra-violet radiation and wide temperature variations. The incident radiation would be greatly enhanced if the trajectory passes through the van Allen radiation belts and the use of a radioisotope or nuclear reactor for power supplies would also increase the ambient radiation intensities.

VI. OPERATIONAL FLEXIBILITY

For manned exploration of the Moon as distinct from unmanned probes, it will be important to provide a measure of flexibility in the navigation and guidance system. Although boost phase guidance, etc., is likely to be entirely automatic, the human navigator must be able to preset the automatic equipment according to the situation. In other words, the human navigator does the overall decision-making and the automatic equipment implements those decisions. To aid him in making his decisions, the human navigator will require the aid of adequate data (such as ephemerides of the

Moon and Earth) and computing facilities. These could be based on Earth (or Moon), but this goes against the principle of self-containment and brings in the problems of communication involving time-lags of up to 1·3 sec. for a one-way link. A vehicle-borne computer with adequate data storage would not only increase overall safety as discussed earlier, but also allow considerable flexibility.

Almost certainly such a computer would have to be digital in nature in order to handle the large quantities involved with sufficient accuracy. With present-day techniques, using transistors and printed circuits, only a small volume, weight and power supply would be demanded. An example of what can be done now is the VERDAN computer made by Autonetics in U.S.A. This is partly a general-purpose computer (handling whole numbers) and partly a digital differential analyser (handling increments only). Its capacity and speed can be judged by the fact that the D.D.A. part alone can process 128 variables every hundredth of a second, and yet the whole computer[34] takes up only 1½ ft.³

With a flexible, accurate and reasonably high-speed computer of this type available, all the navigation and guidance equipment can be integrated into one efficient system. A central computer of this kind could process the inertial data from the accelerometers, including integration and gravity compensation. It could reduce the results of astronomical fixes to estimates of position and velocity and it could also incorporate the data received from ground stations. Furthermore, it could be used by the crew members as a general-purpose computer for the solution of any particular arithmetical problem that should arise.

A block diagram of a possible integrated system of this kind is shown in Fig. 6. The various computer blocks may in fact be separate pieces of equipment or some of the various functions may perhaps be performed by one computer on a time-sharing basis.

No mention has yet been made of terminal guidance. Various proposals have been made in this connection[25,31] and no doubt optical, radio and radar techniques will all find application here. Whatever the system, it will be desirable to integrate it with the other equipment. No attempt has been made to incorporate terminal guidance in Fig. 6, since this needs a fuller discussion than can be given here. However, whenever attitude and velocity changes are required during the terminal phases, whether it be for injection into a closed orbit or a re-entry corridor or for soft landing, the inertial equipment can be used for monitoring and control.

Before closing this section, it is worthwhile pointing out that a self-contained inertial system may be the only way in which to control the launch phase from the Moon on a return journey to Earth. This is likely to be the case at least for the early manned expeditions before adequate ground radio stations can be erected on the Moon.

VII. CONCLUSIONS

From this general examination of the navigation and guidance problems involved in lunar flight, it is concluded

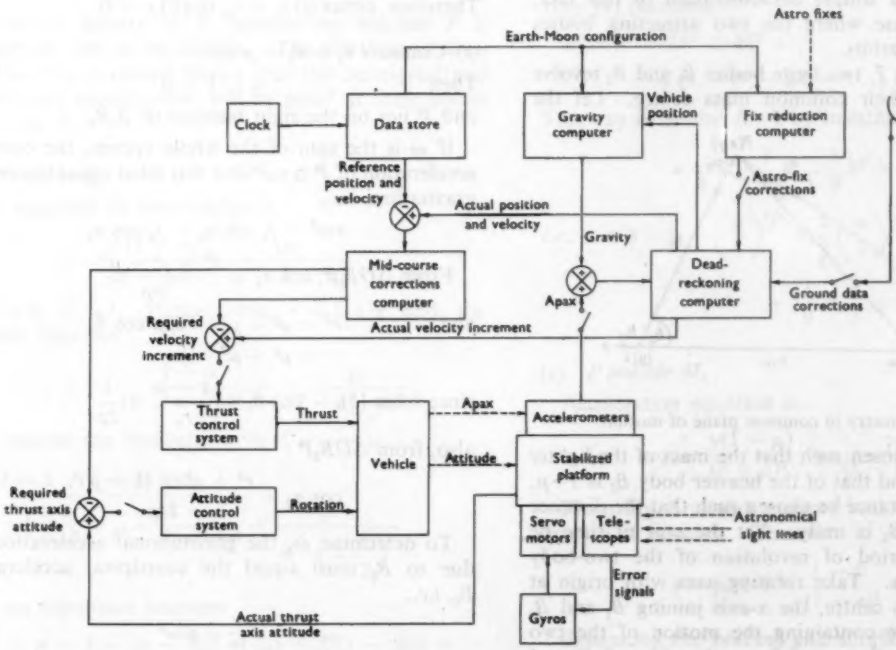

FIG. 6. Integrated navigation and guidance.

that inertial equipment is likely to be employed. Although it could be used during the boost and injection phase from Earth, radio methods of boost guidance are also available. During mid-course correction manœuvres, however, vehicle-borne accelerometers appear to be indispensable for monitoring the manœuvres. From the point of view of overall safety in manned expeditions, it is desirable to have independent navigation systems in order to avoid total reliance on one. A combined optical-inertial system appears to be very suitable as an alternative to ground-based systems. Furthermore, such a self-contained system will increase operational flexibility, and this will be necessary for the more ambitious missions in lunar exploration. It would seem very desirable to integrate all the boost, mid-course and terminal guidance equipments into one overall system, and for this a light-weight, flexible digital computer would be required. Such an integrated, self-contained system would then be capable of providing all the necessary navigation and guidance facilities for flights both ways between Earth and Moon.

APPENDIX

Equilibrium Points in Earth–Moon System

It has been known for more than a century that in a system of two bodies, such as Sun–Jupiter or Earth–Moon there exist five points at which a body of infinitesimal mass can remain in equilibrium (see Fig. 2). The following is a simple demonstration of this fact, for the special case where the two attracting bodies move in circular orbits.

Referring to Fig. 7, two finite bodies B_1 and B_2 revolve in circles about their common mass centre. Let the

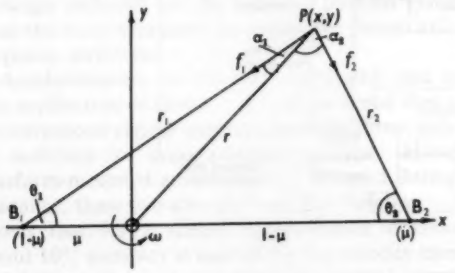

Fig. 7. Geometry in common plane of motion.

unit of mass be chosen such that the mass of the lighter body B_2 is $\mu \leqslant \frac{1}{2}$ and that of the heavier body B_1 is $1-\mu$. Let the unit of distance be chosen such that the distance between B_1 and B_2 is unity. Let the unit of time be such that the period of revolution of the two-body system is 2π units. Take rotating axes with origin at the common mass centre, the x-axis joining B_1 and B_2 and the x-y plane containing the motion of the two bodies. The co-ordinates of B_1 are then $(-\mu, 0, 0)$ and those of B_2 are $(1-\mu, 0, 0)$.

For a small third body P to remain in equilibrium relative to B_1 and B_2, the centripetal acceleration at P must equal the combined gravitational attractions of B_1 and B_2. This implies that P must lie in the plane of motion, for otherwise there will be gravity components normal to the plane of motion which cannot be equated to any component of centripetal acceleration.

Let P be at the point (x,y). The first requirement is that the net gravitational acceleration must be towards O, towards which the centripetal acceleration is directed. Referring to Fig. 7, the gravitational accelerations are

$$f_1 = \frac{\gamma(1-\mu)}{r_1^2} \text{ towards } B_1$$

$$f_2 = \frac{\gamma\mu}{r_2^2} \text{ towards } B_2$$

It is required that $f_1 \sin\alpha_1 = f_2 \sin\alpha_2$ .. .. (1)

But from ΔOB_1P

$$\frac{\sin\alpha_1}{\mu} = \frac{\sin\theta_1}{r} = \frac{1}{r} \cdot \frac{y}{r_1}$$

$$\therefore \sin\alpha_1 = \frac{\mu y}{rr_1} \quad .. \quad .. \quad .. \quad (2)$$

Similarly

$$\sin\alpha_2 = \frac{(1-\mu)y}{rr_2} \quad .. \quad .. \quad .. \quad (3)$$

From (1), (2) and (3)

$$\frac{\gamma(1-\mu)}{r_1^2} \cdot \frac{\mu y}{rr_1} = \frac{\gamma\mu}{r_2^2} \cdot \frac{(1-\mu)y}{rr_2}$$

Therefore, either (*i*) $r_1 = r_2$, or (*ii*) $y = 0$ .. .. (4)

(*i*) Consider $r_1 = r_2 = \rho$ say.

Then $$x = \tfrac{1}{2} - \mu \quad .. \quad .. \quad (5)$$

and P lies on the right bisector of B_1B_2.

If ω is the spin of the whole system, the centripetal acceleration of P is $r\omega^2$ and this must equal the resultant gravitation, *i.e.*,

$$r\omega^2 = f_1\cos\alpha_1 + f_2\cos\alpha_2 \ldots \quad .. \quad (6)$$

From ΔOB_1P, $\cos\alpha_1 = \dfrac{r^2+\rho^2-\mu^2}{2r\rho}$

and $$r^2 = \rho^2 + \mu^2 - 2\rho\mu\cos\theta_1$$
$$= \rho^2 + \mu^2 - \mu$$

since from (5), $\cos\theta_1 = \dfrac{x+\mu}{r_1} = \dfrac{1}{2\rho}$

also, from ΔOB_2P

$$\cos\alpha_2 = \frac{r^2+\rho^2-(1-\mu)^2}{2r\rho}$$

To determine ω, the gravitational acceleration at B_1 due to B_2 must equal the centripetal acceleration at B_1, *i.e.*,

$$\frac{\gamma\mu}{1^2} = \mu\omega^2$$

$$\omega^2 = \gamma$$

Evaluation of Eq. (6) and simplification yields

$$\rho = 1 \quad .. \quad .. \quad .. \quad (7)$$

since $r \neq 0$. Hence P must lie at the two points forming equilateral triangles with B_1 and B_2 (see P_4 and P_5 in Fig. 2).

(*ii*) If $y = 0$, P must lie on the x-axis. If r is the distance of P from O, the centripetal acceleration is $r\omega^2 = r\gamma$ directed towards O. The magnitude and

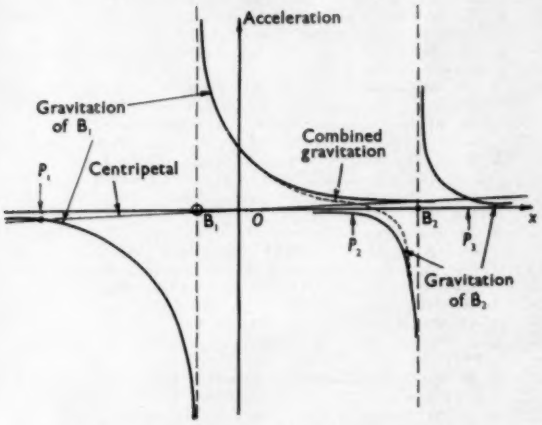

FIG. 8. Accelerations acting in straight line case. (Plot of acceleration along negative X-axis vs. position coord. X).

direction of gravity at P depends on whether P is between B_1 and B_2 or outside. The situation is illustrated in Fig. 8, which shows that the centripetal and gravitational accelerations will be equal at three points P_1, P_2 and P_3.

(*a*) *P outside* B_1

The equation of acceleration is

$$r\gamma = \frac{\gamma(1-\mu)}{(r-\mu)^2} + \frac{\gamma\mu}{(r+1-\mu)^2}$$

as $\mu \to 0$, $r \to 1$. Hence write $r = 1 + \epsilon$ and the equation becomes

$$1 + \epsilon = \frac{1-\mu}{(1+\epsilon-\mu)^2} + \frac{\mu}{(2+\epsilon-\mu)^2}$$

To expand the brackets, write $\xi = \epsilon - \mu$.

Then $r = 1 + \xi + \mu$ and

$$1 + \xi + \mu = \frac{1-\mu}{(1+\xi)^2} + \frac{\mu}{4\left(1+\frac{\xi}{2}\right)^2}$$

which on expansion becomes

$$1 + \xi + \mu = 1 - \tfrac{3}{4}\mu - \xi(2 - \tfrac{1}{4}\mu) + \xi^2(3 - \tfrac{43}{16}\mu) - \\ - \xi^3(4 - \tfrac{31}{8}\mu) + \ldots$$

hence $\tfrac{1}{4}\mu = -\xi(3 - \tfrac{1}{4}\mu) + \xi^2(3 - \tfrac{43}{16}\mu) + \\ + \xi^3(4 - \tfrac{31}{8}\mu) + \ldots$

This can easily be solved for ξ by an iterative process, giving

$$\xi = -\frac{7}{12}\mu - \frac{7^2 \times 23}{12^4}\mu^3 + 0(\mu^4)$$

$$i.e., \quad r = 1 + \frac{5}{12}\mu - \frac{7^2 \times 23}{12^4}\mu^3 + 0(\mu^4) \quad .. \quad (8)$$

(*b*) *P between* B_1 *and* B_2

Accleration equation is

$$r\gamma = \frac{\gamma(1-\mu)}{(r+\mu)^2} - \frac{\gamma\mu}{(1-\mu-r)^2}$$

From Fig. 8 we can expect $r = 1 - \mu - \epsilon$ where ϵ is small and positive.

$$\therefore 1 - \mu - \epsilon = \frac{1-\mu}{(1-\epsilon)^2} - \frac{\mu}{\epsilon^2}$$

Expanding the bracket and simplifying,

$$(3 - 2\mu)\epsilon^3 = \mu - (1-\mu)\{3\epsilon^4 + 4\epsilon^5 + \ldots\} \quad (9)$$

Hence, for small μ, ϵ is approximately $(\mu/3)^{1/3}$.

Write

$$\lambda = \left(\frac{\mu}{3}\right)^{1/3}, \; i.e., \; \mu = 3\lambda^3 \quad .. \quad .. \quad (10)$$

then (9) becomes

$$\epsilon^3 = \lambda^3 + 2\lambda^6 + 4\lambda^9 + \ldots \\ \ldots - \tfrac{1}{3}[1 - \lambda^3 - 2\lambda^6 - \ldots][3\epsilon^4 + 4\epsilon^5 + \ldots]$$

This can be solved for ϵ by iteration, giving

$$\epsilon = \lambda - \frac{1}{3}\lambda^3 - \frac{1}{9}\lambda^3 + 0(\lambda^4)$$

$$i.e., \; r = 1 - \mu - \left(\frac{\mu}{3}\right)^{1/3} + \frac{1}{3}\left(\frac{\mu}{3}\right)^{2/3} + \\ + \frac{1}{9}\cdot\frac{\mu}{3} + 0\left(\frac{\mu}{3}\right)^{4/3} \quad .. \quad (11)$$

(*c*) *P outside* M_2

Acceleration equation is

$$r\gamma = \frac{\gamma(1-\mu)}{(r+\mu)^2} + \frac{\gamma\mu}{(r-1+\mu)^2}$$

From Fig. 8 we can expect $r = 1 - \mu + \epsilon$ where ϵ is small and positive. Therefore

$$1 - \mu + \epsilon = \frac{1-\mu}{(1+\epsilon)^2} + \frac{\mu}{\epsilon^2}$$

Expanding the bracket and simplifying,

$$(3 - 2\mu)\epsilon^3 = \mu + (1-\mu)\{3\epsilon^4 - 4\epsilon^5 + \ldots\} \quad .. \quad (12)$$

Hence $\epsilon = (\mu/3)^{1/3}$ approximately. Making the substitution (10), equation (12) becomes

$$\epsilon^3 = \lambda^3 + 2\lambda^6 + 4\lambda^9 + \ldots$$
$$\ldots + \tfrac{1}{3}\,[1 - \lambda^3 - 2\lambda^6 - \ldots]\,[3\epsilon^4 - 4\epsilon^5 + \ldots]$$

Solving for ϵ by iteration,

$$\epsilon = \lambda + \frac{1}{3}\lambda^2 - \frac{1}{9}\lambda^3 + 0(\lambda^4)$$

$$i.e., r = 1 - \mu + \left(\frac{\mu}{3}\right)^{1/3} + \frac{1}{3}\left(\frac{\mu}{3}\right)^{2/3} - \frac{1}{9}\left(\frac{\mu}{3}\right) + $$
$$+ 0\left(\frac{\mu}{3}\right)^{4/3} \quad .. \quad (13)$$

For the particular case of the Earth–Moon system, $\mu = 0{\cdot}01216$, the unit of distance is 238,900 miles and the unit of time is $27{\cdot}32/2\pi = 4{\cdot}35$ days. Substituting these values in (8), (11) and (13) gives the position of the straight line equilibrium points as

$$B_1P_1 = 0{\cdot}993 \text{ units} = 237{,}200 \text{ miles},$$
$$B_2P_2 = 0{\cdot}1505 \text{ units} = 35{,}950 \text{ miles},$$
$$B_2P_3 = 0{\cdot}1674 \text{ units} = 40{,}000 \text{ miles}.$$

It can be shown that the points P_1, P_2 and P_3 are points of unstable equilibrium. The equilateral points are points of stable equilibrium if $\mu < \frac{1}{2} - (23/108)^{1/2} = 0{\cdot}0385$. In the case of the Earth–Moon system, this is so. For the simple model examined, therefore, the equilateral points are stable. In practice, however, the eccentricity of the Moon's orbit and planetary and solar perturbations must also be included. It is not certain whether in fact the equilateral points are stable or not.

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SURFACE NAVIGATION ON THE MOON*

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(Communication from Hawker Siddeley Aviation Ltd.)

ABSTRACT

This paper commences by discussing likely landing sites for Phase 1 (Short-Range) and Phase 2 (Medium-Range) exploration teams, followed by some of the special problems inherent in lunar navigation. An outline of the preparatory work required for navigational purposes prior to lunar landings is given. This includes cartography and photographic survey; the design of special navigational equipment (optical, inertial, radar); and the use of navigation/communications satellites. An analysis is made of suitable navigation systems for Phase 2 exploration and survey parties.

Finally, sample expeditions to Tycho (Phase 1 type) and to the Mare Imbrium (Phase 2 type) are examined.

I. INTRODUCTION

It would appear that early lunar exploration will take place in two phases. The first phase will consist of point landings at selected sites and the second phase will consist of area investigations which can be likened to the transantarctic overland expedition.

In the author's opinion, suitable sites for point landings in the first phase would be as a first choice the crater Tycho, notable for its prominent ray system, and as a second choice a site in the Mare Imbrium, to be used later as the base for the second-phase expedition.

Tycho is a crater in the south of the Moon and has a diameter of 50 miles. The ray system of which it is the centre extends over the visible surface of the Moon This crater is by far the most prominent, and at full Moon is one of the brightest objects. It has walls 12,000 ft. high which are terraced and it contains a central hill.

The north-western shore of the Mare Imbrium is not far from the epicentre of one of the main events in lunar evolution, the Imbrium impact. In the north-western bay of the Mare Imbrium and within easy access of one another across the lava flow are a number of unique features:

Plato—an interesting, large, old-type crater with a dark floor of diameter 60 miles.

The Alpine Valley—a great gorge that divides the Lunar Alps and is oriented toward the Imbrium impact epicentre.

Pico and *Piton*—two isolated mountains of heights 8,000 and 7,000 ft. respectively, of different material from the Mare Imbrium itself.

Mt. Blanc—one of the highest peaks of the Lunar Alps, at 11,600 ft.

Cassini—a very complex crater containing two subsidiary craters, Cassini "A" and "B". Within Cassini "A" is an interesting smaller crater with two central pits.

Palus Nebularum—containing a good example of a "rill."

Aristillus—an example of a crater with a central mountain and a small ray system.

Archimedes—a crater with a flat floor about 50 miles in diameter and of comparable age to Plato.

An analysis of a large-scale expedition based in the Mare Imbrium has been considered elsewhere.[1]

II. SPECIAL PROBLEMS IN LUNAR NAVIGATION

The environment peculiar to the Moon poses its own particular navigational problems.

The diameter of the Moon is only 2160 miles, compared with the Earth's diameter of 7914 miles. This reduces the distance to the horizon and it can be seen from Fig. 1 that an object would need to be 1000 ft. high to be visible to a 6-ft. man at a distance of 22 miles, or 10,000 ft. high to be just visible at a distance of 65 miles.

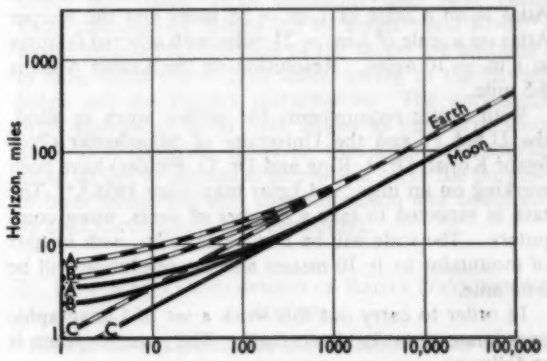

FIG. 1. Range of lunar visibility.
Observation heights: A. 18 ft., B. 6 ft., C. 0 ft.

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A more serious difference between terrestrial and lunar conditions lies in the lack of a useful ionosphere or radio wave reflecting layer (the present evidence on the lunar ionosphere has been discussed by Herring and Light[2]). Hence, for radio communication only line-of-sight transmission at normal frequencies can be used, and owing to the lunar curvature its range will be much reduced.

A third important difference is the relative weakness of the lunar magnetic field. Navigational equipment based on a north-seeking reference is therefore virtually useless.

III. EXPEDITION PREPARATION

1. Lunar Cartography and Survey

Before any lunar expedition can be mounted there is a considerable amount of groundwork to be carried out in the analysis of navigational philosophies and the development of suitable navigational equipment.

One of the prime requisites of any expedition is a set of large-scale maps of the landing area and terrain within exploration range. These may be produced either by drawings at the telescope or from photographic plates.

Telescopic maps of the Moon began with Galileo (1610), continued with Hevelius (1647) and Riccioli (1651) and ended with those of Elgar (1895) and Wilkins (1960). The map by Wilkins is on a scale of 1 in. = 55 miles.

Photographic atlases of note are those by Schmidt (1879), Loewy and Puiseux (The Paris Atlas, 1900) and Kuiper (Photographic Lunar Atlas, 1959). The Paris Atlas is on a scale of 1 in. = 55 miles and the Kuiper Atlas on a scale of 1 in. = 21 miles with selected features at 1 in. = 10 miles. Resolution on the Kuiper Atlas is 0·5 mile.

With future requirements for surface work in mind, the U.S.A.F. and the University of Manchester (Professor Kopal, Dr. J. Ring and Dr. G. Fielder) have been working on an improved lunar map since 1958.[3,4] The task is expected to take a number of years, using computers. The scale will be 1 in. = 15 miles, with heights of mountains to ± 10 metres and the resolution will be 0·62 mile.

In order to carry out this work a set of Lunagraphic coordinates must be determined. The present system is as follows:

> From the Earth, the Moon is seen to librate (or rock) both up and down, and from side to side. The zero meridians of both latitude and longitude pass through the mean centre of libration of the visible disk. This coordinate system and the lunar features themselves must, however, all be correlated with fine accuracy. Previously these were tied to peaks such as Mt. Piton, but this has been found inaccurate and a system is now proposed using the numerous shallow craters as control points. The centres of these craters can be very accurately determined.

The limiting factor for Earth-based photographic programmes is the resolution that may be obtained. Under fair conditions the limit of resolution is 1 mile, owing to scintillation of the Earth's atmosphere.[5] Under good seeing conditions, however, 0·4 mile may be obtained photographically.

Dr. Ring is working on a telescope photoelectric attachment for use in the Manchester University programme; it is designed to trigger the camera at the moment of best seeing. The visual resolving power of a trained observer under the best atmospheric conditions is assessed at 0·1 mile.[6]

A method of obtaining greater detail was proposed by Merton E. Davies[7] and this employs a lunar orbit satellite to photograph the surface in a similar fashion to *Lunik III*. The resolution would be 0·09 mile and 0·75 mile with 24-in. and 3-in. focal length lenses respectively. Other proposals of a similar nature have been made.[8,9]

It has been stated recently[10] that three parallel feasibility study contracts have been awarded by N.A.S.A. (J.P.L.) to Eastman Kodak, Fairchild and Radio Corporation of America for a lunar orbiting photographic satellite. This programme is known as V.O.I.S. (Visual Observation Instrumentation Subsystem) and caters for photographic mapping of the Moon to a resolution of 0·062 mile for the entire map and 0·006 mile for selected areas.

It may be of interest at this point perhaps to mention a difference in terminology which has become apparent during the preparation of this paper. All maps of the Moon to date have been produced for the use of the astronomer. Obviously, up till now there has been no requirement for a map to be used by an astronaut on the lunar surface itself. Consequently, on all lunar maps north is at the bottom as it would appear in a refracting telescope and the east and west correspond to terrestrial east and west, not lunar east and west. Thus it would appear that two types of map are required, one for astronomers and one for astronauts.

2. Special Navigational Equipment

For both the first and second phases of early lunar exploration some development work must be carried out on navigational aids. The point landings will require only limited equipment, such as: a celestial prismatic sighting upon the Sun, Earth or Pole Star; numbers of lightweight portable transceivers or relays; a ground current telegraphy set; and seismic communicators. A typical set of equipment is shown in Fig. 2.

North-Seeking Instrument

Another north-seeking device could be developed based on the principle of north-finding using a watch. As will be remembered, for terrestrial work one uses a watch giving local mean time. When one requires information on a north-south position line, the hour hand of the watch is pointed at the Sun. The angle

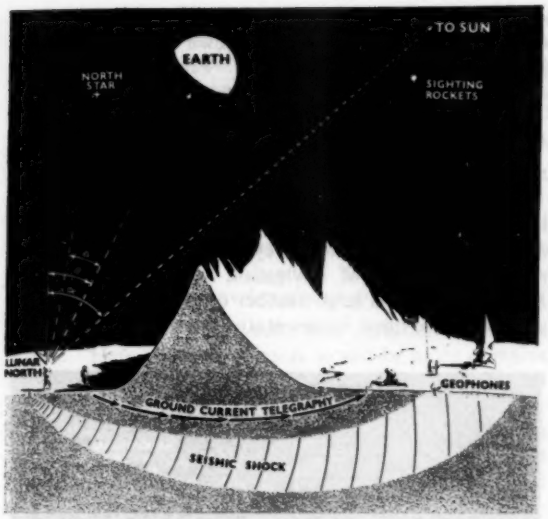

FIG. 2. Navigational techniques for small parties.

between the hour hand and the noon position on the dial is then bisected. This bisector gives the north-south line. This may be explained as the Sun "appearing" to rotate about the Earth once in 24 hours, whereas the clock hand rotates twice in 24 hours. The zero may be taken each day at noon when the hour hand is at 12 o'clock and the Sun is due north (Southern Hemisphere).

For lunar travel, one would need a "clock" graduated in lunar time; *i.e.*, to make two revolutions in 28 calendar days. It would need a tripod to provide a rigid base and a telescope complete with graduated scale, to measure the azimuth angle of the Sun. For lining the "hour" hand up with the Sun one would need a prismatic viewer. The same procedure could then be applied as for terrestrial use.

Inertial Navigation Equipment

For second-phase expeditions it would be necessary to develop inertial navigation equipment capable of being employed under conditions of rough usage. Automatic solar- or nuclear-powered position-monitoring equipment such as Racon/DME sets* must also be developed for extended use with no maintenance.

Navigation/Communications Satellite Systems

Another navigational/communications aid required is a system of active repeater satellites in lunar orbits. These satellites, of which there should be a sufficient number (probably four in a 200-mile circular orbit), would provide sufficient coverage for the second-phase expedition.

The expedition would land at lunar daybreak, and in the first period of light, automatic stations for determining the orbital elements of these satellites would be set up at Piazzi Smyth base and Mt. Piton. During the first dark period, this determination would be carried out for the first time and the information would be updated continually during the course of the expedition.

The use of the navigational satellites would be similar in all respects to the "Transit" system. The computed orbital elements would be transmitted to the satellite and read out every minute or so on one of the two Doppler frequencies.

Other navigational information would be the two constant frequencies for doppler shift determination and a time reference. The doppler data (already vacuum), would then be obtained from the two transmitted signals, and a computer would determine the latitude and longitude of the surface vehicle.

Such a system operating on frequencies of 200 and 400 Mc./sec. with a power output of only 100 mW. has been described.[11] One of its attractive features for lunar use is that no prior north reference is required and positional accuracies of $\frac{1}{2}$ mile can be obtained.

It may be of interest here to mention the improbability of a satellite corresponding to the Earth's 24-hour synchronous satellite. Using the method of Greenwood[12] we find that such a satellite would revolve at a distance of 54,000 miles from the centre of the Moon and well beyond the null point of 23,600 miles. It would thus be well within the region where the Earth's gravity field predominates and would be unstable. This is mainly because of the large period of rotation, which is 648 hours on the Moon compared to 24 hours on Earth.

There are also indications that other lunar satellite orbits may suffer from instability and swift decay. From calculations carried out by Singer[13] and Kooy[14] it would appear that satellites of the Moon are unstable if in close orbit below 2160 miles, owing to the Moon's bulge and the Earth's perturbation. The only stable orbit appears to lie at right angles to the Earth-Moon line. It is probable, however, that a powered satellite using an ion or plasma engine would serve the purposes of both navigation and communication and could also be used for lunadesy (or selenodesy).

3. Design and Development of Radar Navigational Systems

The radar equipment for use in second-phase exploration will be used from the surface exploration vehicle. There are a number of inherent differences between terrestrial and lunar radar problems.

For good angular resolution, the highest possible frequency (or smallest possible wavelength) should be used, as this enables a narrow beam to be obtained with a small aerial. The beamwidth is inversely proportional to the aerial size in wavelengths. On the Earth, attenuation by atmospheric gases increases with frequency. Oxygen has a resonance at 60,000 Mc./sec. resulting in

* Racon/DME = RAdar beaCON/Distance Measuring Equipment, passive until interrogated (see later in paper).

an attenuation of 20 db./km.; water vapour has a resonance at 25,000 Mc./sec., with an attenuation of 0·2 db./km. In addition, serious losses can occur through rain and fog; these may amount to as much as 10 db./km. in really heavy rain, at frequencies between 30,000 Mc./sec. and 100,000 Mc./sec. It is therefore necessary to reach a compromise between resolution of the picture and loss of range due to these effects, since in practice the aerial size is limited by mechanical considerations.

For marine radar, a frequency of 10,000 Mc./sec. (wavelength 3 cm.) is normally used. Atmospheric attenuation is less than 0·02 db./km. in good weather at this frequency, though it may rise by a factor of ten in heavy rain. However, practical aerial apertures of 5–10 ft. result in beamwidths of 0·5–1°. In the vertical plane, a somewhat larger beam-width (10–20°) is normally used, to minimise the effect of rolling of a ship. The highest frequency used for radar at present is 35,000 Mc./sec. This is used at London Airport for a high-resolution picture of the airport itself, but the maximum range required here is only 1 mile. In bad weather only the larger passenger aircraft can be detected at this range. In good weather pedestrians can be seen.

On the Moon, atmospheric effects should be completely absent, and we can use a much higher frequency than on Earth. Present techniques would limit the frequency to about 50,000 Mc./sec. (wavelength 6 mm.), which would enable a 0·1° beam to be produced with a 10 ft. aerial. A wider beamwidth in the vertical plane would probably be used, as in marine radar. By 1970, the likely date of such an expedition, higher frequencies may have been exploited, which would enable narrower beams to be produced without any increase in aerial size.

As frequency increases, dimensional tolerances on aerials become tighter and on Earth this sets a limit (at about 0·1°) to the narrowness of the beam which can be obtained. The lower gravity on the Moon and absence of wind should make larger aerials, and hence narrower beams, a more feasible possibility.

A further factor that has to be taken into account is the effect of dust. This will not form clouds, but the smaller particles may persist sufficiently to affect the radar equipment. It is possible that an operating frequency might have to be chosen to give minimum returns from dust clouds, but such studies are dependent on a knowledge of composition and particle size.

With respect to range resolution, if the equipment is intended mainly for surveillance use, it would probably be a pulsed radar system. The accuracy of a pulsed radar can be a few metres. This is quite adequate for survey work at long ranges. Discrimination of echoes of similar size on the same bearing but of different range is determined by the pulse width, and it is unlikely that objects with a separation of less than 15–20 m. could be distinguished with a pulse width of 0·05 μsec., which may be regarded as the minimum which can be achieved in the present state of the art.

This is obviously inadequate for use as a close-range navigational aid during the lunar night in a terrain which, for example, may be strewn with rocks comparable in size with the vehicle. For this purpose, an optical (or perhaps infra-red) system will be required.

4. The Choice of Navigation System for Phase 2 Expeditions

The choice of navigation system for this type of expedition should be carefully made as it must also have the capability for use in a survey role at a later date. A representative list of navigation systems is shown in Fig. 3. There is a large number of possible systems and some of those most representative are outlined here.

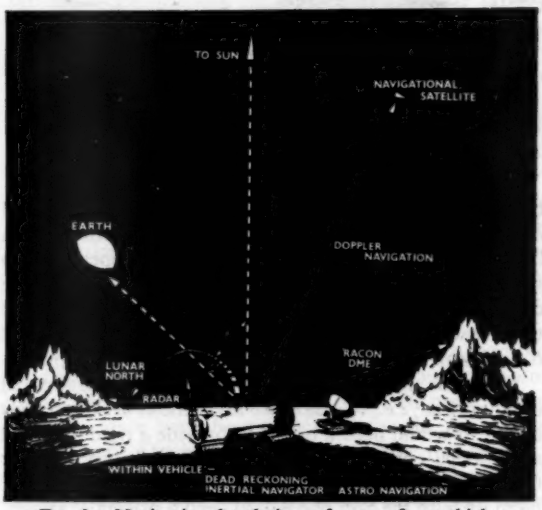

Fig. 3. Navigational techniques for a surface vehicle.

System No. 1. The simplest possible system: a small medium-frequency (M.F.) beacon is placed at the control point and a direction-finding loop is carried in the vehicle. A north reference is supplied in the vehicle by inertial or other means. Errors could be high but the large amount of experience which has been accumulated in this field makes it reasonably certain that most errors could be minimized. Range with M.F. is better than with V.H.F., being up to 100 miles with powers of 50 W. or thereabouts. With this system only the bearing is obtained; no distance information is given. However by taking bearings from two points and knowing the distance to one point from the beacon and the track of the vehicles the position of the second point may be obtained geometrically with fair accuracy.

System No. 2. This system employs D.F. (direction finding) combined with distance-measuring equipment. In place of the M.F. beacon we employ a miniature transponder, and the north reference is again supplied from the vehicle. The return time of the radar pulse gives distance of the transponder from the vehicle. Such a transponder could be miniaturized and made

easily portable. The system would operate on V.H.F. and would thus be restricted to optical range. A prepared baseline could be employed and a series of triangulations employed. This would dispense with a north-seeking reference supplied by the vehicle and could be used for survey purposes later.

System No. 3. This would employ the vehicle radar set in combination with the miniature transponders. The presentation in the vehicle could give distance and bearing. The vehicle inertial guidance would provide the north reference. This could give very good accuracies at millimetric wavelengths or quasi-optical ranges.

System No. 4. This would be a variation on System No. 3. Here the transponders would be more complex and would be orientated upon installation with respect to north. They would be capable of discriminating the bearing of the incoming signal either by a rotating antenna or by virtue of its polar diagram. Upon interrogation, information would be supplied on distance and bearing with respect to north. Other local conditions could also be telemetered upon interrogation to the main vehicle such as temperatures, incident radiation level, etc. This system is shown in Fig. 2 as *Racon/DME*.

System No. 5. Long-range aids, *i.e.*, Decca systems. These are really too large for early exploration work but capable of high accuracy. It is possible, however, that special propagation effects caused by the large number of charged particles existing on the lunar surface and ferrous deposits may create problems both with such a navigation system and the electronics of the vehicle itself. Low-frequency receivers are particularly prone to static interference and the high charge which has been suspected to exist on the lunar surface might be troublesome in this respect.

5. Navigation Systems for Phase 2 Survey Parties

In order to commence a lunar survey, a baseline of, say, 5 miles would probably be set up running due north. This would be prepared using astronomical sightings or the navigation/communications satellites in lunar orbit and the length of the baseline would be known to a high accuracy. Transponders would be set up on the baseline having an integral time delay of known and fine calibration.

A direction-finding and distance-measuring antenna on the vehicle would also be required. This would enable a triangulation to be made.

It is suggested that an operating frequency of about 1200 Mc./sec. could be used. Each transponder could be identified by a coding system employing a number of pulses. The first pulse of the group would give distance and the remainder would identify the transponder. Voice modulation could allow use as a radio relay to the exploration base. Using the baseline transponders, a programme of terrain mapping could be carried out using high-resolution millimetre radar techniques.

IV. SAMPLE EXPEDITION TO TYCHO: PHASE 1

We may now deal with sample expeditions proposed in Section I. If we assume that a landing is made in Tycho to investigate the ray system, we may also assume that small parties will be sent off into the surrounding mountainous territory to follow the system and collect ray samples from the lunarite* rocks.

As soon as the party leaves the crater, it must have a navigational system. This must be fairly simple and must not require complex equipment. It should be as easy to use as a prismatic compass. This would be the celestial prismatic, "sighting" onto the Earth (which subtends an angle of 2° as seen from the Moon) to obtain a bearing.

At this region in the south of the Moon, the Earth will appear due north. This will be modified by a total libration of 8°, but the exact figures for libration will be available prior to the landing and a north bearing can be obtained.

Another instrument used would be the north-seeking "clock" described earlier.

An interesting question now arises in the use of celestial sightings. Owing to the vacuum environment, all the stars will increase by orders of magnitude and stars at present not visible to the unaided eye will be quite bright. This may create a problem in identifying navigational stars against the greatly increased star field background. However, as all the magnitudes are increased by the same amount the problem may not arise.

Navigational techniques for a small party were shown in Fig. 2. Besides the celestial prismatic, we may use a choice of methods, each of which requires the knowledge of a north reference.

There is for example, the possibility of firing sighting rockets at timed intervals by either base or party. The flares will tend to fall faster because of vacuum and slower owing to the lower gravity, and may thus be equivalent to Earth conditions.

One solution for signalling to the rocket may be by the use of seismic shots, and an array of geophones at the rocket may be able to fix the angle of the shot with reference to a local longitude. A return code could give the required information.

Another method perhaps would employ a technique being developed in the United States by at least two firms.[15,16] This system uses Earth currents or electromagnetic waves instead of relay satellites, and employs buried antennae. The tests which have been carried out include transmissions of signals from a deep mine and reception from the bottom of a lake. Satisfactory results were obtained but the system is unlikely to replace the artificial satellite as the global communications link

* Upland lunar rocks, as distinct from lunabase rocks (mare materials).

of the future, since it is regarded as essentially a short-range technique.

It will probably operate on telegraphy only and on a very low frequency. For lunar work over short distances—as, for example, between individual members of a small exploration team in difficult terrain—this system may prove very useful. Using this type of ground wave, it may be possible also to communicate from the base to the exploration team, probably on a frequency of about 1 Mc./sec. using a 10 ft. aerial, although the conductivity and dielectric constant of the Moon are unknown factors. The question of a return signal from the team is a marginal possibility. It may be possible also to carry a number of miniature relay repeaters which would be put down on the way out and collected on the return.

An integrated system of such aids will probably be used for navigation by small parties in rocky terrain.

V. SAMPLE EXPEDITION TO THE MARE IMBRIUM: PHASE 2

The expedition to this area will use lunar surface exploration vehicles (L.S.E.V's) and Fig. 3 shows an integrated system of navigation using these vehicles.

The basic navigational aid is inertial, supervised at intervals of, say, 3 hours by astronomical shots or information obtained via the communication/navigation satellite network mentioned earlier.

Map reading will, of course, be extensively employed and a surveillance radar will be used for navigation and survey, especially during periods of lunar darkness or earthlight.

The fourth navigational system will be the use of transponders, as mentioned earlier, which upon interrogation will give information on bearing and distance of vehicle from transponder. Similar transponder systems used terrestially are the Racon and D.M.E. systems operating on the 1000 Mc./sec. band. In this system,[17,18] bearing can be given to 1·5° and distance to 0·25 mile.

A 10-week programme for the exploration of the corner of Mare Imbrium has already been suggested; navigational techniques for this are proposed as follows:

During the first week, a landing would be made and the Base Camp organized at Piazzi Smyth crater. As from sunrise to sunset on the Moon is equivalent to a terrestrial fortnight this initial organization would take until lunar midday.

The second week would be taken up with the installation of a Racon-type beacon, satellite tracker, and radio relay on Mt. Piton, the collection of L.S.E.V. capsules from the landing area and preparations for the lunar night.

During the first fortnight of darkness, the L.S.E.V.'s would be assembled and prepared for use, and the system of navigation satellites checked at the lunar surface itself from the base. Very short expeditions requiring no navigational aids would also be conducted during this period.

When the top of Mt. Piton was illuminated by the Sun and dawn commenced to break over the lunar scene, the two L.S.E.V.'s would begin their journeys. Using their inertial, satellite and Racon-type systems, two vehicles ("A" and "B") would lumber off to the west and east respectively.

The ringwalls of Piazzi Smyth are 3500 ft. above the lunar surface and thus should be visible for a distance of 40 miles. The summit of Mt. Pico is 8000 ft. high and should be visible for 60 miles.

For the first 30 miles, vehicle A would derive information from Piazzi Smyth, for the next 10 miles from both Piazzi Smyth and Mt. Pico, and for the last 50 miles navigation would probably be by line of sight to Mt. Pico.

It is possible that the summit of Pico is visible from the top of Piazzi Smyth ringwall, but for the communication system to be effective it would probably be necessary to place an orientated relay on the crest of the intervening pressure ridge.

On arrival at Mt. Pico, a Racon-type beacon and a radiotelephony relay powered by a nuclear or solar package would be placed in orientation on the summit.

The next leg, to the crater Plato, would have line-of-sight navigation to supplement the others. A drowned crater would be examined, Plato would be seismically and electrically investigated and the vehicle would be serviced and replenished with supplies.

Leaving Plato, for the next 50 miles the navigator would have inertial and satellite systems, and the Racon beacon and radiotelephony relay from Mt. Pico. After crossing a pressure ridge, however, the beacon at Mt. Pico would be lost and reliance would be on inertial and satellite systems, supervised by astronavigation. These conditions would exist for two days at the Antarctic nominal progress of 22 miles per day.

During this leg of 100 miles, which would be carried out during a period of lunar night, a radar survey would be made of the neighbouring Lunar Alps. The radar sweep would also give navigational short-range information of obstacles in the path of the vehicle, as visual range would be very short during this darkness period.

At the commencement of the next lunar day, a Racon beacon and radiotelephony relay would be placed in orientation on the summit of Mt. Blanc. Owing to the altitude (11,600 ft.) it would be visible for 75 miles, and together with the Piazzi Smyth, Mt. Pico and Mt. Piton beacons, would give information on position for later expeditions in the Mare Imbrium. The expedition down the Alpine Valley would be by line of sight only, with communications relays strategically placed and collected on the return.

The use of communications satellites in this narrow gorge (about 5 miles wide) may be rather difficult, owing to the surrounding mountains which would reduce the working angle.

The return to Piazzi Smyth would be largely by the use of Racon information for the first 15 miles and line of sight from then onwards.

During this time, the other L.S.E.V. (Vehicle "B") would have set off on its easterly course. On the first leg of its journey to Promontoria Deville and Agassiz, the navigation would be carried out using the Racon beacons on Mt. Piton and Piazzi Smyth as adjuncts to the main systems.

Mt. Piton stands 7000 ft. high and would be visible for a radius of 55 miles, but on approaching the Promontoria, the Piazzi Smyth Racon would go out of range.

The next leg to Cassini would use Mt. Piton together with inertial and satellite navigation. A radar survey of the Southern Lunar Alps would be carried out during the course of the passage.

On arrival at Cassini, this crater would be investigated and the vehicle would then set off for the nearby rill to carry out a lunalogical investigation.

During this part of the journey and the leg to the crater Aristillus, the vehicle would be out of touch with Mt. Piton

and the navigational/communications satellites would be the prime system, assisted by inertial equipment.

The expedition would so far have been carried out during the lunar day and the day would end by the passage to the Aristillus crater and a study of the ray system.

Here the vehicle would again come within range of Mt. Piton and expedition information not relayed by communications satellites would be exchanged. The vehicle would be serviced and replenished from soft-land payloads.

As the lunar night fell, the searchlights would be switched on and the vehicle would move off, using radar to scan the path ahead. A turning point would be made near a small crater and the vehicle would then travel south-west for the Archimedes crater.

When 15 miles from the turning point, the Mt. Piton transmitter would be lost and the next 50 miles would be navigated using radar, inertial navigator and navigational/communications satellites.

A survey could then be made of Archimedes when lunar daybreak occurred. The last leg would begin with a departure to the north-east with a programme of seismic shooting.

On this leg, early navigation would be by communications/navigational satellites, then at about 70 miles out the Piton Racon relay is picked up. Finally at about 40 miles out Piazzi Smyth comes through.

At last, 4 days before the return to Earth, 5¼ weeks after leaving base and after a total navigation of 820 miles the two vehicles would arrive back at Piazzi Smyth.

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DISCUSSION

Dr. E. K. SANDEMAN,* Ph.D. (Fellow): Can Mr. Stewart give us some idea of the temperatures encountered on the Moon?

Mr. P. A. E. STEWART (*in reply*): Estimates of surface temperatures vary widely. The temperature will, of course, depend both on latitude and time of lunar day. From the more reliable published results it appears that at the poles it may vary between 50° C. and absolute zero; at the equator it may rise to 100° C. during the day.

A MEMBER: Has Mr. Stewart considered astronomical methods of navigation, such as the use of a sextant? It should be possible to compile nautical tables for use on the Moon.

Mr. P. A. E. STEWART: There would be difficulties in observing stars.

Mr. C. POWELL†: The tracked vehicles described in Mr. Stewart's paper will entail a vast amount of effort to assemble and operate and even minor damage to them in the early stages might jeopardize the whole operation. It would therefore seem very important to maké a detailed photographic survey of the area of the first expedition in order to build up as clear a picture as possible of the "going" likely to be encountered. This would require low-altitude stereo pairs of photographs, which would presumably have to be taken from a rocket vehicle.

Ground control could later be provided, but a better electronic aid to this than the proposed DME responder would clearly be a microwave line-measurement system of the Tellurometer type.

The selection of a pulse transponder as a navigational aid may have been made on account of misgivings about the effect of magnetic field anomalies upon l.f. or v.l.f. transmissions. It is hard to see, however, how such effects could occur when using these frequencies in the "groundwave" mode of propagation; in view of the need for light and small receiving equipment, and of the restricted line-of-sight distances, the use of l.f. and v.l.f. for navigation would seem well worth considering.

Mr. R. LAW: What is known about meteoric dust on the Moon?

Mr. P. A. E. STEWART: On the basis of Grimminger's study of the hazard of meteoric collisions in space and the data on micrometeorites obtained since by Vanguard I and subsequent satellites, it seems that double-wall shielding should prove adequate against most meteorites likely to be encounted by lunar exploration vehicles. To guard against the possibility of penetration by a meteorite, it is proposed that the vehicle should have three separate airtight compartments, or capsules.

Mr. R. LAW: My query really concerned the possible depths of dust on the Moon and whether it was meteoric or volcanic.

Mr. P. A. E. STEWART: Here again, estimates vary widely, Grimminger suggesting that the depth is measured in millimetres, while Professor Gold thinks it might be miles. The vehicle would be fitted with dust guards, but radar could be used for ground navigation in a dust storm.

Dr. R. d'E. ATKINSON‡, M.A., Ph.D.: I cannot help feeling that it is altogether premature to plan a dated schedule of exploration at this time, and indeed the leader of any expedi-

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tion ought himself to possess more imagination than I personally have been able to see in these plans. The conditions on the Moon may very easily be such that quite different plans would be essential, and the entire efforts of the first party landed may have to be devoted purely to keeping alive, and getting away again on any terms at all. Preferably, of course, getting away with some useful information for future planners; but some of the essential information may be hard to obtain. We must remember that the materials of the Moon's surface are to a large extent unoxidized; samples must be collected and their effects on machinery-parts, and on space-suits, must be investigated, *in vacuo* and in the presence of strong ultra-violet and X-rays; moreover, any traces accidentally brought into a tractor or spaceship will be inflammable, if not actually explosive, and some may well be poisonous. In addition, we do not know how deep the dust-layer is, or how large the pebbles and boulders below it are; our largest telescopes cannot see objects as small as a house. If the dust is 50 ft. deep, the retro-rockets necessary for a "soft" landing may in fact expose a floor of jagged boulders, at the bottom of a 50-ft. crater of almost unclimbable dust; indeed, the slope might be so steep that one dare not shut off the rockets because the dust would slide down again and bury the ship. The expedition which finds this out will want to get away again, from zero velocity but without really landing, and if it succeeds in this it will still face us with some awkward development problems before we can begin to schedule actual tours.

Mr. WALKER§: Has Mr. Stewart consider the parameters for radar for ground navigation? At London Airport where they use a wavelength of 8 mm. and a 0·05-μsec. pulse, the discrimination is one of the highest available: about 25 ft. azimuth and range at about 1 mile. That is good enough for aircraft and vehicles on the runways, but nowhere near good enough on the Moon, where a discrimination of about 5 ft. is needed to avoid crevices, *i.e.*, a pulse length of about 0·01 μsec. and a wavelength of 1 or 2 mm.

Mr. P. A. E. STEWART: I have given some thought to it. There is not so much absorption, because of the absence of atmosphere and clouds, so we could use short-wavelength pulse radar ($\sim$6 mm.).

Mr. L. H. BEDFORD**: Earlier speakers have mentioned the term "groundwave mode" in connection with radio propagation. What is the "groundwave mode"; I should like to query its validity.

Mr. C. POWELL: There is no ionosphere and hence no skywave, but it has been suggested that a reflecting layer may exist above the lunar surface as a result of the effect of solar radiation upon the magnetic field. My point was that, on Earth, it is only the reflected mode of transmission that is affected by the magnetic field; on the Moon, a radio navigation system operated at distances of the order which are normally associated with the groundwave mode of propagation should be able to use l.f. or v.l.f. without difficulty.

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GENERAL DISCUSSION

Dr. J. G. PORTER,* B.Sc., Ph.D.: I must begin by expressing some concern at the lack of collaboration between the experts. It seems that no two workers in this field use the same units or the same notation. It is understandable that a new subject should call for a new language and a new method of approach, but there is nothing new in perturbation theory. The methods of Lagrange and Encke have proved their worth over a century and a half, and the principles involved, and the notations employed, are standardized in our textbooks. We may have to change the units (although there is no agreement even here as to the best choice), but the methods are already in existence. Dr. Herrick's method is an ingenious modification of the standard approach, and experience has shown that it is capable of dealing with the most difficult situations. Experience—practical experience—is surely the only real test of any new method. One can demonstrate that the method will work by using imaginary observations (although even this is seldom attempted) but this does not prove very much. In practice one is always faced with the difficulty of dealing with observational errors, and if the observations are few in number, the method of least squares is hardly applicable, and it becomes a very difficult problem to decide which of the observations should be rejected. This is the kind of experience with which the astronomer is already familiar.

The navigator of a spaceship will find many new problems, and although this hardly applies to the comparatively short trip to the Moon, which can be monitored from the Earth, there are some points which call for comment. Space navigation is not a simple matter of determining a fix, although this would be difficult enough. The real problem is to find the velocity of the spaceship, and there is no simple, straightforward method for doing so with any accuracy. Every angular measurement will be affected by aberration, which is continuously changing in an elliptical orbit. Yet the velocity must be known in order to calculate the thrust required to change course, or to predict a time of arrival at the destination. Inertial systems take no account of the gravitational field, and the effect of this must be calculated and combined with the accelerometer readings. Yet this gravitational force is also a function of position, so that it would appear that no single system of navigation in space is self-contained; we must use a combination of several methods. Here, too, I think, we need a great deal more experience!

Dr. R. d'E. ATKINSON,† M.A., Ph.D.: I would like to ask Mr. Cashmore whether the equilateral points referred to in his paper are stable even with elliptical orbits.

Mr. D. J. CASHMORE,‡ M.Sc., A.M.I.E.E. (Fellow): The matter is dealt with in an appendix to the paper to be published. This had to be omitted from the verbal presentation. It is not certain whether the points are stable in the Earth—Moon system.

Dr. J. G. PORTER: I too am not at all happy about these "points of equilibrium" in the Earth—Moon system, although they certainly exist in the case of Jupiter, where the Trojan planets form two stable groups at 60° from Jupiter and from the Sun. However, here the perturbations shift the Trojan planets very great distances—millions of miles—from the theoretical points of equilibrium. In the less massive Earth—Moon system the disturbances would be even greater. It would be a big problem putting the "beacons" there—something like balancing a billiard ball on a needle, or having a cup of tea in a British Railways train.

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Mr. D. J. CASHMORE: If the beacons are approximately stable, it may be convenient to fit them with small rocket motors and monitor them from the Earth, so as to keep them permanently in a suitable position in the Earth—Moon system.

Dr. J. G. PORTER: Who is going to calculate their position? The Nautical Almanac Office?

Mr. R. E. ROBERSON,* B.S. (Fellow): I would like to side with Mr. Cashmore over this. As regards the question of ability to deliver a vehicle to within a small position and velocity error about the stable equilibrium points, I would like to mention that rendezvous studies have indicated the ability to do just this in the immediate neighbourhood of the Earth, *i.e.*, to effect contact of two space vehicles with a relative velocity of a fraction of a m./sec. This suggests that conditions for capture by a stable equilibrium also could be satisfied in spite of the more remote location from the Earth.

Mr. L. H. BEDFORD: Mr. Cashmore said in his presentation that accelerometers would read zero in free fall, *or nearly*. Was he referring to instrumental errors or to relativity effects?

Mr. D. J. CASHMORE: To instrumental errors.

Commander H. R. HATFIELD,† R.N.: As a surveyor who has listened to the lectures today with great interest, I am a bit concerned that all the proposed methods of measuring a space vehicle's position have been based on electronics, whereas the solar system to which they are to apply is defined (in the various Almanacs) in co-ordinates which have been measured by optical methods.

I would like to ask all the speakers whether this optical and "angular" solar system will fit their electronic and linear one?

Dr. J. G. PORTER: It is perfectly true that our knowledge of distances in the solar system is far from being precise, but this does not matter to the astronomer, who is interested only in angles. The angular co-ordinates do not change, if the scale of the solar system alters. In space travel, of course, it is the distances that are important, and this is why it is better to use rectangular co-ordinates in these calculations—to use geometry, in fact, rather than trigonometry.

Commander H. R. HATFIELD: I agree that the x, y, z, system of co-ordinates is a very reasonable one to use. My only worry is that electronic measurements may not fit a solar system which has been defined over the years by observations made visually.

Mr. F. P. HELLER‡: I cannot see a valid reason to assume a difference between the optical and the electromagnetic universe, since the optical universe is electromagnetic. I also cannot agree with the opinion that the speed of a space vehicle can be derived from star observations, since there is no such thing as velocity in space, but only velocity relative to bodies not too far distant.

Commander H. R. HATFIELD: It is a fact that electronic and angular measurements of the same distances in the triangulation of Great Britain do not agree. The snag is that all electronic devices which seem to measure distance, make a basic measurement of time, which has to be multiplied by an assumed velocity or speed of propagation to give distance. Without a very good knowledge of the physical properties of the transmission path this velocity, and hence the distance, may well be in error.

Dr. J. G. PORTER: There is also a discrepancy between the measurements of distance in the solar system, as made by the astronomer and by radar methods. There seems to be no adequate explanation for this anomaly so far. But this is only one of the many problems facing the space navigator. I have already referred to the practical difficulties of velocity determination, but even simple optical measurements, made from a moving space vehicle—for example, the stabilized platform mentioned by Mr. Cashmore—would be subject to serious errors caused by aberration.

Mr. D. J. CASHMORE: For stabilizing a platform in space by gyro, controlled by three starlock telescopes, the effects of aberration can be much reduced. The vehicle velocity (relative to the Sun) will be known approximately, and appropriate electrical biases can be inserted into each telescope. This will reduce the aberration error to a very few seconds of arc even if the velocity is known only to say 10% accuracy. As regards any possible discrepancy between electromagnetic and optical measurements, radar reflections from the Moon here shown that this is not a serious problem in the Earth—Moon system.

Dr. R. d'E. ATKINSON: I am sorry to find myself disagreeing with Dr. Porter and with Mr. Cashmore, but I do not think that stellar aberration poses any real problem at all. It is quite true that the Sun and all other stars are in motion, and their apparent places depend on the motion of the observer; but the places actually recorded in our catalogues are correct (except for a small known term arising from the eccentricity of the Earth's orbit) for an observer stationary with respect to the Sun, no matter how the Sun itself is moving. Any motion of an observer relative to the Sun merely distorts the picture systematically, in a way that does not involve the individual stellar motions themselves at all. Thus if the three angles defined by any three stars are measured, their differences from the catalogue values will suffice to determine the two co-ordinates of the apex of the relative motion, and its magnitude; and the accuracy, though it may perhaps not be adequate for predicting the observer's future path, is inevitably adequate for computing the aberration-corrections of all other stars at that moment at least provided the three stars are chosen so that the variables are well separable. Indeed, as I suggested in a discussion held in this room just 10 years ago, the direction and magnitude of the velocity can be almost as accurately determined in this way as they can by differencing successive fixes.

Mr. R. E. ROBERSON: In connection with Dr. Porter's concern about determining position and velocity in space, I would like to remark that it is not always essential to do this Although some guidance concepts require it, others do not. For example, under some circumstances it may be possible merely to establish orientation (say by reference to two stars, with appropriate allowance for aberration), using a clock and sensitive accelerometer for any low-thrust periods. The resulting guidance concept can carry the vehicle to within a reasonable range of the target for a terminal mode which again dispenses with absolute position and velocity in favour of relative measurements.

Dr. J. G. PORTER: Even sensitive accelerometers have an error of 1 in $10^5 g$.

Mr. R. E. ROBERSON: On Earth, yes. The error has been reduced to 1 in $10^9 g$ in space.

Mr. J. D. BARR‡: Mr. Cashmore postulated a mid-course correction in which he specified an accuracy requirement of 10%. I am surprised that he thought an inertial navigation system would be worthwhile for this purpose. I agree that the direction of the impulse must be controlled, but I would have thought that its magnitude could be controlled to within 10% by an open-loop method.

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Mr. D. J. CASHMORE: The 10% accuracy quoted for the mid-course correction applies only to the simple mission of impacting anywhere on the Moon. For more sophisticated missions, for example reaching a specific point on the Moon within close tolerance, the required accuracy will be higher.

Dr. GILBERT FIELDER†, B.Sc., Ph.D., F.R.A.S. (Fellow): I do agree with Dr. Porter's view that experts in different fields should collaborate more. My subject is the Moon and I have been very surprised by some of the things which have been said about the Moon this afternoon. Perhaps I may consider two of these things.

First lunar temperatures. We should, before quoting temperatures to the nearest degree without qualification, enquire into the methods used to obtain those temperatures. Temperatures cannot be measured directly: what is measured, after corrections for absorptions in the Earth's atmosphere and at the telescope mirrors, is the total radiation (reflected and emitted) coming from the Moon. In order to convert the appropriate component of this radiant energy into temperatures, one may assume, for example, that the Moon is a body in thermal equilibrium—which it is not. With this assumption, the temperature of a point on the Moon varies, due to the eccentricities of both the Earth's and the Moon's orbits, through a few degrees. However, even if the Moon approximates fairly well to a black-body, the temperatures which have been estimated up to date do not refer to a particular point on the Moon's surface. Even the optical measurements—those made with the smallest limit of resolution—refer to large areas of the Moon's surface containing differing kinds of topography; and, hence, yield very much averaged values. The radio methods of estimating temperatures rest on the assumption that the Moon is a black body in these wavelengths. They usually have angles of resolution of the order of size of the disk of the Moon. These estimates are averaged not only across the curved surface of the Moon, but also in depth beneath the surface, for the radio emission emerges from various depths in the Moon. The temperature-errors quoted for the radio methods frequently lie between 10° and 50°, but the actual errors must sometimes be greater than this because different estimates are not always compatible with one another when the estimated errors and the different frequencies are taken into account.

The slide of Mr. Stewart which depicted temperature-zones parallel to the lunar equator means very little. An object placed to face the sunlight at, say the north pole of the Moon, and then placed on the Moon's equator with the same orientation with respect to the Sun, would bear no relationship to the rather meaningless temperatures shown on that slide. The actual temperature of the object would depend largely on its precise nature—as Mr. Stewart implied in answer to a recent question.

The second point I should like to raise concerns lunar dust. There has been some useful, and much useless, speculation about this. Estimates of the depth of the dust are made from the same optical and radio methods used to estimate temperatures; and are subject to the same limitations. Then one assumes a special model of the Moon's surface layers and adjusts this model until it is found to fit the observations. *One* possible interpretation is that, *on the average*, there is a layer of dust on the Moon, overlying more solid rocks. This does not mean that a particular spot on the Moon's surface will be of a dusty nature. If dust is present, one would expect it ot be deeper in some places than in others. Dust would, for example, be agitated by the action of micro-meteorites and would flow under gravity to the lower parts of the surface.

To sum up, the temperature of the rocks at a particular point on the Moon has simply not been measured, up to date. Secondly, the present experimental evidence is such that one cannot use it to arrive at a value for the thickness of a dust layer at any point on the Moon.

Mr. E. W. PIKE†: As an ex-professional air navigator of the sextant and drift-sight era, I have been fascinated by today's discussion although some of it was completely over my head. It seems that the problem of navigating to the Moon is entirely a question of, to use the President of the Institute's words in his recent address, "finding the way." If so, I would like to ask whether the engineers working on space navigation have decided yet how the work is to be conducted. In other words, whether it is to be largely done by remote control from the ground using airborne sensors telemetering information to digital computers working in association with radar tracking, or will the man in space have some control over navigation decisions and control during the voyage. Personal experience of the early days of air navigation gives me a strong intuitive feeling that it would be more prudent to use the intelligence and physical qualities of the men in the vehicle to the fullest possible extent, even though this means replacement of the sextant by much more complex sensors, and the slide rule by the airborne digital computer. If man's freedom to navigate the vehicle is restricted mainly by inability to carry enough fuel for step corrections during the flight, I would think the right course is to look for better fuels for regular course and velocity corrections, otherwise I would feel that the first astronauts would have to be very hardy (not to say foolhardy) individuals.

Is it really too difficult to "find the way" by the tried combination of astronomical knowledge, accurate observation at regular intervals and the judgment of an experienced human navigator?

Mr. D. J. CASHMORE: I have great sympathy for the idea of simplifying space navigation as far as possible. In general, however, the numbers involved are so large and the accuracy required is so high that it is not clear how the problems can be solved with such simple equipment as the speaker suggests.

Mr. E. E. DWECK‡: Mr. Cashmore appears to imply in some of his slides that an I.C.B.M. and a lunar spaceship are in fact two different aspects of the same problem. I just would like to point out that although an I.C.B.M. and a lunar spaceship present close technological affinities their respective problems are somewhat different on both mathematical and psychological grounds and would require a different approach. Indeed, there is no articulate awareness in Dr. Cashmore's approach of the problem of motion reversibility which is of some importance particularly when one considers that the question is not so much to go to the Moon as how to come back. Lastly, I would like to agree wholeheartedly with Mr. Pike who intuitively feels that an astronaut should have a simple instrument like the sextant "to orient himself in outer space."

Mr. J. D. BARR: I was most impressed by Mr. Stewart's proposed expedition and by the amount of detailed consideration he had given. I would like to ask him if he has calculated the cost of the expedition?

Mr. P. A. E. STEWART: No. I am afraid it would be astronomical!

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MINIMUM ENERGY ENTRY INTO ORBITS AROUND MERCURY*

By S. W. GREENWOOD,† M.Eng., A.M.I.Mech.E., A.F.R.Ae.S., Member of Council.

ABSTRACT

The velocity requirements for entry into circular orbits around Mercury are determined, assuming transfer along a substantially cotangential semi-ellipse from Earth, and making allowance for the eccentricity and inclination of the orbit of Mercury. It is shown that the lowest velocity requirement is obtained when the transfer orbit is in the plane of the orbit of Mercury with arrival at perihelion of Mercury's orbit. The same transfer technique is preferred when entry is to be made into a parabolic orbit close to the planet's surface.

IT has been indicated in an earlier note by the author[1] that for each planet there is a circular satellite orbit, entry into which calls for the minimum total velocity requirement. In these earlier studies, it was assumed that the orbits of the planets were circular, concentric and coplanar, and transfer was effected along a minimum energy semi-ellipse.

The planet for which it appeared to be of greatest advantage to take account of this effect was Mercury. With the single exception of Pluto, for which these studies are of only academic interest, Mercury is the planet with an orbit having the greatest eccentricity (0·206) and inclination (7°). Further studies were therefore carried out to investigate the influence of these factors on the results obtained for this planet.

From the viewpoint of simple computation, it is a convenience that perihelion and aphelion of the orbit of Mercury lie close to the ecliptic. For these studies, the assumption is made that these points lie in the ecliptic. The various alternative flight paths open to us are, of course, infinite in number, but only the four bounding possibilities listed below were examined, transfer in each case being effected along a substantially cotangential semi-ellipse:

(1) Correct for inclination of orbit of Mercury in departing from Earth, and so enter a transfer orbit in the plane of the orbit of Mercury. Arrive at Mercury's perihelion.

(2) As (1), but arrive at Mercury's aphelion.

(3) Enter a transfer orbit in the ecliptic, and correct for inclination of orbit of Mercury when reaching Mercury. Arrive at Mercury's perihelion.

(4) As (3), but arrive at Mercury's aphelion.

The main results of these studies are presented in Table I, alongside corresponding data for the simplified study based on circular, concentric coplanar orbits for the planets. The circular orbit considered around Mercury is that closest to the surface, since this gives the minimum total velocity requirement in each case.

As expected, transfers to Mercury's perihelion involve a more eccentric transfer orbit than those to the planet's aphelion, and the velocity requirements for departure

TABLE I.—*Breakdown of velocity requirements (in miles/sec.) for flights from Earth to orbit of Mercury and to close circular orbits around Mercury respectively, with transfer in the orbital planes of Earth and Mercury respectively, and with arrival at perihelion and aphelion respectively of the orbit of Mercury.*

	Data based on simplified model of circular, concentric, coplanar orbits	Data allowing for eccentricity and inclination of orbit of Mercury			
		Transfer orbit in Earth orbit plane		Transfer orbit in Mercury orbit plane	
		Arrival at perihelion	Arrival at aphelion	Arrival at perihelion	Arrival at aphelion
Escape from Earth and enter transfer orbit	8·34	9·02	7·84	9·22	8·10
Enter orbit of Mercury distant from planet	6·00	6·60	8·21	4·60	7·50
Enter circular orbit around Mercury close to surface	4·67	5·23	6·74	3·42	6·08
Total for entry into orbit of Mercury distant from planet	14·34	15·62	16·05	13·82	15·60
Total for entry into circular orbit around Mercury close to surface	13·01	14·25	14·58	12·64	14·18
Saving	1·33	1·37	1·47	1·18	1·42
Saving, % of total	9·3	8·2	9·2	8·5	9·1

* Manuscript received 1 December, 1960.

† Writer and Consultant, 2 Tower Walk, Weston-super-Mare, Somerset.

from Earth and entry into these transfer orbits are correspondingly higher. The requirements at perihelion are seen to be lower than at aphelion. The total requirements for entry into the close circular orbit around Mercury are roughly the same for all cases except that for transfer in the orbit plane of Mercury and arrival at the planet's perihelion. For this case the velocity requirement is significantly lower, and is usefully lower than that indicated in the simplified study that ignored the inclination of the planetary orbits.

The preferred transfer orbit is thus in the plane of the orbit of Mercury with arrival at the planet's perihelion. The percentage saving possible through entry into a close circular orbit around the planet is 8·5, a little less than that previously indicated in the simplified study, but still very useful.

The situation for arrival at Mercury's perihelion is illustrated in Fig. 1. The transfer takes 96·5 days, just

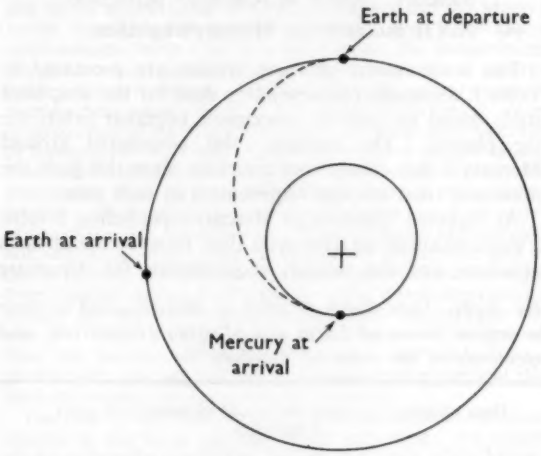

FIG. 1. Earth-to-Mercury transfer orbit. The situation illustrated is for arrival at Mercury's perihelion.

over three months, and the relative position of the two planets and the Sun on completion of the transfer is shown. This should favour communication with the minimum interference from solar noise.

For the most suitable case, the velocity requirements for entry into circular orbits around Mercury at different distances from the planet are given in Fig. 2.

Similar studies to the above were carried out for entry into parabolic orbits around Mercury following transfer along a substantially cotangential semi-ellipse, for direct comparison with the simplified studies of an earlier note

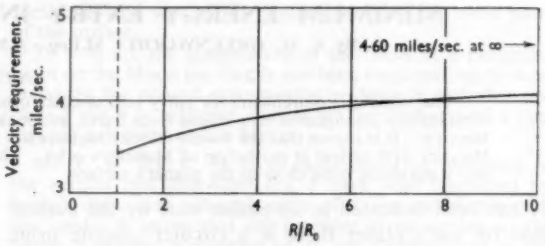

FIG. 2. Velocity requirement for entry into circular orbit around Mercury from transfer orbit. The transfer orbit is in the Mercury orbit plane, and arrival is at Mercury's perihelion.

by the author.[2] Again, it was found that the minimum total velocity requirement is given by transfer in the orbit plane of Mercury with arrival at perihelion. The main results are compared in Table II.

TABLE II.—*Comparison of simplified and real velocity requirements (in miles/sec.) for flights from Earth to orbit of Mercury and to close parabolic orbit around Mercury respectively. The real case shown is that giving the lowest total velocity requirement.*

	Data based on simplified model of circular, concentric, coplanar orbits	Data allowing for eccentricity and inclination of orbit of Mercury. Transfer orbit in Mercury orbit plane. Arrival at perihelion
Total for entry into orbit of Mercury distant from planet	14·34	13·82
Total for entry into parabolic orbit around Mercury close to surface	12·22	11·86
Saving	2·12	1·96
Saving, % of Total	14·8	14·2

A conclusion of both sets of studies is that the assumption of circular, concentric, coplanar planetary orbits is satisfactory for introductory consideration of the total velocity requirements for entry into orbits around other planets, though more realistic assumptions will obviously be required for more advanced studies.

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CORRESPONDENCE

The First Astronauts

SIR,

On reading the *Journal* for March-April 1961, I found reference to Commander David Shepard. The name of America's first astronaut was Alan Bartlett Shepard, Jnr.

I was pleased to hear that the B.I.S. awarded a gold medal to Major Gagarin. Incidentally, the publication *U.S.S.R.* spells the Major's name Yuri Alexeyevich Gagarin, unlike the spelling which appeared in your editorial.

Tomorrow America hopes to send Air Force Capt. Virgil I. (Gus) Grissom into space. His "back-up man" is Marine Lt.-Col. John H. Glenn, Jnr. I hope that you will, in the future, be able to accurately report the names of America's spacemen.

As a point of interest, within less than 24 hours of this writing, America will have successfully launched and retrieved two astronauts. At least the U.S.A. will then have had more men in space than Russia!

Sincerely,
(Miss) RUTH CUMMINGS.

194, Campbell Avenue,
Williston Park,
Long Island, N.Y., U.S.A.

18 *July*, 1961.

We must offer our apologies to Cdr. Shepard for the error mentioned by Miss Cummings. With regard to the Russian astronaut, we gave his name as Yurii Alekseevich Gagarin, as he calls himself Юрий Алексеевич Гагарин. *Admittedly there are several systems of transliteration from the Cyrillic, but for uniformity we use only one in the* Journal, *namely the "British System." This is used by the British Academy, the British Standards Institution, and most scientific societies in this country. It is very close to that used by the American Chemical Society* (in Chemical Abstracts) *and is likely to be adopted by the American Standards Association. Most "cover-to-cover" translations of Russian scientific journals use the system; the most important body not employing it is the Library of Congress, which would like to change to the British System, but cannot afford to.*

Stationary Satellites

SIR,

I appreciate Mr. Mustelin's comments[1] on my short paper on Stationary Satellites.[2] He is quite right to point out that, in the case of a planet with bound rotation, the gravitational field of the Sun can readily be taken into account. That it affects the orbital radius by as much as 30% is certainly significant. I had not realized that the modification was so large, and I am grateful to Mr. Mustelin for drawing attention to this.

As far as the major planets are concerned, Mercury is the only one with bound rotation. I agree with the reduced figure of 137,000 miles for the orbital radius of a stationary satellite given by your correspondent. This, however, is still as high as 88 times the radius of the planet, and my conclusion that it would be too far out to be of practical value for communication purposes still holds.

I am stimulated by Mr. Mustelin's reference to such a body situated above the shadow side of Mercury to offer a suggestion for a practical application of a different kind. He points out that the satellite would receive a certain amount of solar radiation, and could thus use solar batteries. A simple calculation shows that about 89% of the Sun's face would be obscured by the planet (at its mean distance from the Sun) and that the energy received would be about 77% of the energy that would be received in the region of the Earth's orbit.

We are thus presented with an opportunity for observing the solar limb and corona at fairly close range, with the main body of the Sun blocked out by an atmosphereless planet and while in receipt of no more than comfortable amounts of radiant energy. Such a satellite could well become a useful tool for solar research.

Yours sincerely,
S. W. GREENWOOD.

2, Tower Walk,
Weston-super-Mare, Somerset.
13 *February*, 1961.

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Minimum Energy Entry into Planetary Satellite Orbits

SIR,

In Mr. Greenwood's paper of the above title,[1] the author is mistaken in supposing that: "it is an effect that appears to have escaped attention hitherto."

The existence of these optimum orbits was demonstrated by Ehricke,[2] whilst the periods, radii, and velocity saving for both Mars and Venus were given in a paper of mine.[3] The problem was also analysed by Lawden[4]; oddly enough, he came to an incorrect conclusion, finding that the most economical transfer was by two impulses into the largest possible circular orbit.

It is worth quoting these earlier studies, not only to establish their priority, but also to show how difficult it is to find any aspect of astronautics which has not already been given some consideration.

Yours faithfully,
C. A. CROSS.

225, London Road,
Northwich, Cheshire.

2 *July*, 1961.

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NEWS AND ANNOUNCEMENTS

B.I.S. NEWS

Symposium on Materials in Aerospace Technology

A symposium on Materials in Aerospace Technology is being organized by the Society and will be held in the Lecture Theatre of the Royal Aeronautical Society, 4, Hamilton Place, London, W.1, on Wednesday, **22 November, 1961**, from 10 a.m. to 5 p.m.

The provisional programme is as follows:

9.30 a.m.	Opening Remarks, by Chairman (Dr. W. R. Maxwell, President of the Society).
9.45 a.m.	"A General Survey of the Materials Problem," by A. J. Murphy (Principal, College of Aeronautics).
10.15 a.m.	"Polymers in space", by A. L. Soden (Rubber and Plastics Research Association of Great Britain).
10.45 a.m.	*Coffee.*
11.00 a.m.	"Magnesium in Spaceflight", by Dr. C. J. Smithells (Magnesium Elektron Ltd.).
11.30 a.m.	"Aluminium and Its Alloys", Dr. E. G. West (Technical Director, Aluminium Development Association).
12.00	*Discussion.*
1.00 p.m.	*Luncheon Break.*
2.30 p.m.	High-Strength Steels", by F. J. Wilkinson (Bristol-Aerojet Ltd.)
3.00 p.m.	"The Development of Nozzle Materials", by Dr. D. Bunting (Rocket Propulsion Establishment, Ministry of Aviation).
3.30 p.m.	"The Use of Graphite Materials in Aerospace Technology", by R. K. Hurden (Morganite Exports Ltd.) and A. E. White (Morganite Research and Development Ltd.).
4.00 p.m.	*Tea.*
4.15 p.m.	"The Effect of the Radiations Encountered by Materials in space", by Dr. R. S. Barnes (United Kingdom Atomic Energy Authority).
4.45 pm.	*Discussion.*

The symposium is open to members of the Society without charge; non-members may attend on payment of a registration fee of £2 2s. 0d. Both are requested to register in advance if possible; forms are obtainable from the Secretary, British Interplanetary Society.

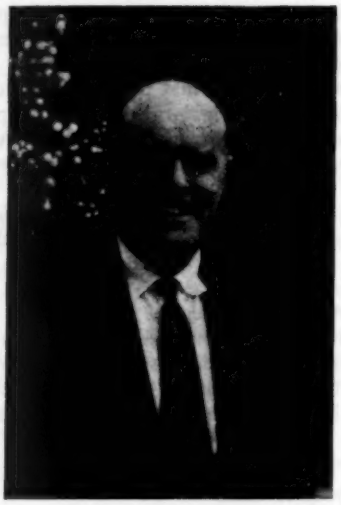
OBITUARY

Stewart Scott Hall

Mr. Stewart Scott Hall, C.B., died in Melbourne on 3 August at the age of 56. This news came as a great shock to all who knew him, particularly to his friends in the aviation community.

As his contemporary at the Imperial College of Science and Technology, I remember Scott Hall as a student—highly gifted, but modest and unassuming; his subsequent career confirmed this early impression.

Starting at Royal Aircraft Establishment, Farnborough, in 1927, Scott Hall went on to AEE at Martlesham Heath and then to Orford Ness in 1937. After a further spell at R.A.E. during the war he was promoted in 1946 to the post of Principal (later General) Director of Technical Development at the Ministry of Supply.



In 1953 he went to U.S.A. as Head of the Ministry of Supply Staff at the British Joint Services Mission. His tour of duty in Washington was a great success and his technical competence and personal qualities won him many friends in America. From 1956 to 1959, Scott Hall was Scientific Adviser to the Air Ministry and then took up his last post, that of Head of the U.K. Defence Research and Supply Staff in Australia.

He was permanently immersed in a complex atmosphere of civil service and "official" science, but never lost his interest in new ideas and trends. He attended Astronautical Congresses; only a few years ago this sort of independent thinking was not popular with Government Departments, almost frowned upon as something verging on the subversive.

Scott Hall, though highly competent and enthusiastic in his work, was not a narrow-minded specialist. He had many outside interests and took up painting seriously during his stay in America. This venture emphasized the versatility of his nature and capacity to achieve success in fields of activity totally unrelated to his day-to-day work.

The British Interplanetary Society owes a great deal to Scott Hall for his unremitting efforts to affirm and expand its influence in Australia. Even after his serious illness and operation in 1960 he carried on his work as Secretary of the Victoria Group of the Society. He joined the Society in March, 1958, and was later elected to the Fellowship. He was also a Fellow of the Royal Aeronautical Society, and of the City and Guilds Institute.

All his friends will remember Scott Hall as a man of great intellectual integrity—a rare phenomenon in these days of pressure salesmanship and brainwashing. His life's work, dedicated to the interests of British avaition, will remain an example to those who will succeed our generation in the new and wider fields of aerospace science and technology.

As a personal note, I should like to add that those who knew him have lost a staunch and loyal friend, a true gentleman in word and deed.

M. N. GOLOVINE

ASTRONAUTICAL ABSTRACTS

Edited by J. HUMPHRIES

1961-62 PART 4

Abstracting panel:

C. FLEISHER, J. FOLEY, HAWKER SIDDELEY AVIATION LTD.; ADVANCED PROJECTS GROUP, C. E. S. HORSFORD, J. HUMPHRIES, A. E. SLATER, G. V. E. THOMPSON, E. WHITE

A complete list of journals abstracted together with abbreviations used is to be included in the 1959-60 index.

The following abstracts refer to books noted in this issue: 1007, 1032.

1—ASTRONOMY

.1 *General*

(977) **Vistas in radio astronomy.** W. L. Rae. *Spaceflight*, **2**, 83–90 (*July*, 1959). Possible use in studying radio suns and their relation to the origin of cosmic rays, extending the observable universe, 21-cm. observation of galactic structure, and investigation of planetary radio noise. (46 *refs.*)

(978) ***Mechta* radiation data.** S. N. Vernov, A. E. Chudakov, P. V. Vakulov and Yu. I. Logachev. *Astronautics*, **4** (7), 23, 86–8 (*July*, 1959). Data on cislunar corpuscular radiation and the Van Allen belts, obtained by *Mechta* and *Sputnik III*.

(979) **Radio astronomical measurements from Earth satellites.** A. C. B. Lovell. *Proc. Roy. Soc. A*, **253**, 494–500 (29 *Dec.*, 1959). (16 *refs.*) Gives examples of difficulties encountered in making observations on the Earth which could be overcome by use of satellite-mounted apparatus: scintillation effects, low-frequency cut-off, etc. Some possible investigations are outlined.

.4 *Sun*

(980) **Observational astrophysics from rockets. I. Nebular photometry at 1300 Å.** J. E. Kupperian, A. Boggess and J. E. Milligan. *Astrophys. J.*, **128**, 453–64 (*Nov.*, 1958).

(981) **Solar ultraviolet spectroscopy from rockets.** R. Tousey and J. D. Purcell. Paper read at *Optical Soc. Amer.* 1959 *Annual Mtg.* (1959).

.5 *Planets (except Earth)*

[*See also* abstract no. 1064]

(982) **Observations of Jupiter, Saturn, and Venus, in 1958.** A. P. Lenham. *J. Brit. Astronom. Soc.*, **69**, 163–7 (*May*, 1959).

(983) **What kind of a world is Jupiter?** R. S. Richardson. *Griffith Observer*, **23**, 88–91 (*June*, 1959).

(984) **Further evidence of vegetation on Mars.** W. M. Sinton. *Science*, **130**, 1234–7 (6 *Nov.*, 1959). (8 *refs.*)

(985) **Dissipation of planetary atmosphere.** V. A. Firsoff. *Science*, **130**, 1337–8 (13 *Nov.*, 1959). (4 *refs.*)

.7 *Moon*

[*See also* abstract no. 1064]

(986) **Effect of the solar wind on the lunar atmosphere.** J. R. Herring and A. L. Licht. *Science*, **130**, 266 (31 *July*, 1959). (11 *refs.*)

2—PHYSICS

.1 *General*

[*See also* abstract no. 1048]

(987) **Self-contained measuring equipment for electron density and ionic mass spectrum.** J. Sayers. *Proc. Roy. Soc. A*, **253**, 522–5 (29 *Dec.*, 1959). Two experiments instrumented at the University of Birmingham for rocket installation, which could be useful (in a modified form) for satellite instrumentation.

(988) **Some techniques of physical measurement.** R. L. F. Boyd. *Proc. Roy. Soc. A*, **253**, 516–22 (29 *Dec.*, 1959). Making use of the vehicular motion (X-ray emulsion detectors, photography, magnetometers, telescopes, etc.); Langmuir probes and their use in studying electron energy distributions and in mass analysis of ions present in the upper atmosphere.

.5 *Heat and Thermodynamics*

(989) **A photographic study of boiling in the absence of gravity.** R. Siegel and C. Usiskin. *J. Heat Transfer*, **81C**, 230–6 (*Aug.*, 1959).

.6 *Electricity and Magnetism*

(990) **Methods of measuring magnetic fields.** E. Barber. *Calif. Inst. Technol., Pasadena, Jet Propulsion Lab. JPLAI/LS-195*, 22 pp. (3 *March*, 1960). Bibliography on methods of measurement from a space vehicle. (134 *refs.*)

(991) **A relation between ionospheric drifts and atmospheric dynamo current systems.** L. H. Heisler. *Austr. J. Phys.*, **13** (2), 188–91 (*June*, 1960).

.7 *Cosmic Radiation*

(992) **Study of the cosmic-ray soft component by the 3rd Soviet Earth satellite.** S. N. Vernov *et al. Planetary and Space Sci.*, **1**, 86–93 (*April*, 1959).

(993) **Satellite observations on solar cosmic rays.** P. Rothwell and C. McIlwain. *Nature*, **184**, 138–40 (18 *July*, 1959). (11 *refs.*)

(994) **Radiation observations with satellite 1958 δ over Australia.** A. J. Herz, K. W. Ogilvie, J. Olley and R. B. White. *Nature*, **184**, 391–5 (8 *Aug.*, 1959). Records of radio signals received from *Sputnik III* (which carried a scintillation counter), with partial analysis. The counter had a high detection efficiency for low-energy photons.

(995) **Experiments on cosmic radiation by means of artificial satellites.** C. F. Powell. *Proc. Roy. Soc. A*, **253**, 482–7 (29 *Dec.*, 1959). Advantages compared with balloon experiments.

.8 *Other Upper Atmosphere Phenomena*

(996) **Results of temperature measurements by *Explorer I*.** *Luftfahrttechnik*, **4**, 178 (*June*, 1958). (*In German.*)

(997) **Cloud-cover and other meteorological infrared measurements from an Earth satellite.** G. Stroud. Paper read at *Optical Soc. Amer.* 1959 *Spring Mtg.* (1959).

(998) **Rocket spectroscopy; airglow and aurora observations.** R. Tousey. Paper read at *Optical Soc. Amer.* 1959 *Spring Mtg.* (1959). Review of Soviet work.

(999) **The sun and the upper atmosphere.** H. Friedman. *Astronautics*, **4** (7), 20–2, 55–6 (*July*, 1959). Discoveries made by rocket astronomy.

(1000) **Density of the upper atmosphere from analysis of satellite orbits; further results.** D. G. King-Hele. *Nature*, **184**, 1267–70 (24 *Oct.*, 1959). (23 *refs.*)

(1001) **Geomagnetically-trapped corpuscular radiation.** J. A. Van Allen. *Proc. Roy. Soc. A*, **253**, 525–9 (29 *Dec.*, 1959). Bibliography. (58 *refs.*) Paper originally given at meeting was published elsewhere (*J. Geophys. Res.*, **64**, 271–286 (1959)).

(1002) **Some problems concerning the terrestrial atmosphere above about the 100 km. level.** D. R. Bates. *Proc. Roy. Soc. A*, **253**, 451–62 (29 *Dec.*, 1959). Significance of recent rocket and satellite studies relating to the thermosphere. Unless H atoms are being captured rapidly from interplanetary space they must be very rare at the base of the exosphere. The importance of the steepness of the temperature gradient above the *E* layer is emphasized. Ionizing radiation from the Sun is considered to be the main source of heat. An analytic model of the thermosphere is appended. (57 *refs.*)

(1003) **Interplanetary space and the Earth's outermost atmosphere.** S. Chapman. *Proc. Roy. Soc. A*, **253**, 462–81 (29 *Dec.*, 1959). Theoretical discussion of the static temperature distribution in the solar corona. The influence of hot coronal gas on the Earth's outermost atmosphere is discussed. (60 *refs.*)

(1004) **Determination of upper-atmosphere air-density profile from satellite observations.** G. V. Groves. *Proc. Roy. Soc., A*, **252**, 16–27 (25 *Aug.*, 1959). A solution is obtained for the rate of change of semi major axis and perigee distance of a satellite orbit with time due to the resistance of the atmosphere. The logarithm of the air density (ρ) is assumed to vary quadratically with height (h) and the oblateness of the atmosphere is taken into account. Calculation of perigee ρ in terms of rate of change of satellite period is discussed and the method applied to data available for *Sputniks I* and *II*, *Vanguard I*, and *Explorers I*, *III* and *IV*, giving $\ln \rho = -28{\cdot}59\ (\pm 0{\cdot}15) - (h-200)/46\ (\pm 5) + 0{\cdot}028\ (\pm 0{\cdot}013)\ (h-200)^2/(46)^2$ for $170 \leqslant h \leqslant 700$ km., with h in km., ρ in g. cm.$^{-3}$; the standard deviations are given in parentheses. (13 *refs.*)

(1005) **Discovery of electrons with an energy of about 10 keV. in the upper atmosphere with the aid of the third Earth satellite.** V. I. Krasovskii, I. S. Shklovskii, Yu. I. Gal'perin and E. M. Svetlitskii. *Technical Trans. F-39, Office of Technical Services, Dept. of Commerce, Washington, D.C., U.S.A.*, 7 pp. (*June*, 1960). Also available as 60–21182, NRL Trans–774, 7 pp. (*Dec.*, 1959). $0.50. [Translated from *Doklady Akad. Nauk S.S.S.R.*, **127** (1), 78–81 (1 *July*, 1959).]

4—BIOLOGY AND MEDICINE

.1 *General*

(1006) **Logistic support to man's ecology in space.** J. E. Mangelsdorf. *A.S.M.E. Prepr.* 59–*AV*–56, 24 pp. (1959). (8 *refs.*)

(1007) **The new frontier.** K. G. Williams. 21s., 176 pp. *Heinemann, London* (1959).

(1008) **The chemical origins of life.** M. H. Briggs. *Spaceflight*, **2**, 69–73 (*July*, 1959). Surveys present views. (27 *refs.*)

(1009) **Bibliographic control of aviation and space medical literature.** A. J. Jacobius. *Aerospace Med.*, **30**, 507–16 (*July*, 1959). Presented at 30th Annual Mtg. of Aero Med. Assoc. [For abstract see abs. no. 1914, *J.B.I.S.*, **17**, 340 (*May–June*, 1960).] (69 *refs.*)

.2 *Botany*

(1010) **What is astrobotany?** G. A. Tikhov. *Spaceflight*, **2**, 74–7 (*July*, 1959). Work of Department of Astrobotany, Academy of Sciences Kazakh S.S.R., Alma-Ata, in studying possibility of vegetation on Mars and Venus, and in investigating fluorescence of plants.

.4 *Anatomy and Physiology*

(1011) **Symposium on space medicine.** *Aeroplane*, **95**, 660 (31 *Oct.*, 1958). Report on B.I.S. symposium (*J.B.I.S.*, 1959–60, **17**, 279–324).

(1012) **The present status of the problem of weightlessness.** P. A. Campbell and S. J. Gerathewohl. *Texas State J. Med.*, **55**, 267–74 (*April*, 1959).

(1013) **Space feeding: big $$ market.** J. Baar. *Missiles and Rockets*, **5** (25), 28, 32 (15 *June*, 1959). Notes on work being done by various U.S. firms for the U.S.A.F.

(1014) **Human pilot performance during boost and atmosphere re-entry.** R. C. Kaehler. *Aerospace Med.*, **30**, 481–6 (*July*, 1959). (3 *refs.*)

(1015) **Calculations of the radiobiologic risk factors in nuclear-powered space vehicles.** E. P. Konecci and R. Trapp. *Aerospace Med.*, **30**, 487–506 (*July*, 1959). Presented at 30th Annual Mtg. of Aero Med. Assoc. [For abstract see abs. no. 1935, *J.B.I.S.*, **17**, 340 (*May–June*, 1960).] (31 *refs.*)

(1016) **Food; space age problem.** *J. Agricultural and Food Chem.*, **31**, 600–4 (*Sept.*, 1959).

(1017) **Rotating ball simulates satellite flight.** Northrop Corp. *Prod. Engng.*, **31** (44), 17 (24 *Oct.*, 1960). 10-ft. dia. fibreglass ball designed for use in investigating man's reaction to complex rotation in space.

5—AVIATION AND AERODYNAMICS

.2 *Aerodynamics*

(1018) **The use of aerodynamic lift during entry into the Earth's atmosphere.** L. Lees, F. W. Hartwig and C. B. Cohen. *A.S.M.E. Prepr.* 59–*AV*–36, 16 pp. (1959). (5 *refs.*)

(1019 **Long period oscillations during atmospheric entry.** G. S. Campbell. *ARS J.*, 525–7 (*July*, 1959). Presents an approximate theory for the oscillatory characteristics of the long-period motion during atmospheric entry at constant lift and drag coefficients. Comparison with numerical results for the complete equations of motion indicates that the approximate theory provides an accurate description of the time-varying amplitude decay and frequency during entry.

(1020) **Hypervelocity vehicles at large angles of inclination.** W. H. T. Loh. *ARS J.*, 522–3 (*July*, 1959). Complements results for small angles of inclination and constant lift/drag ratio obtained by A. J. Eggers and H. J. Allen (NACA TN 4046, Oct., 1957).

(1021) **Analysis of the aerodynamic heating for a re-entrant space vehicle.** M. J. Brunner. *J. Heat Transfer*, **81C**, 223–9 (*Aug.*, 1959). (9 *refs.*)

(1022) **The penetration of planetary atmospheres.** C. Gazley. *J. Heat Transfer*, **81C**, 315–22 (*Nov.*, 1959). (8 *refs.*)

.3 *Rocket-Propelled Aircraft*

(1023) **X-15, a performance study.** "Bisonius." *Aeroplane*, **95**, 730–4 (14 *Nov.*, 1958).

(1024) **Adaptive servomechanisms and the X-15 inertial reference system.** S. Cap. *Sperry Engng. Rev.*, **13** (3), 12–19 (*Oct.*, 1960). Concept of the self-adjustment of control systems to accommodate environmental changes.

6—ASTRONAUTICS

.1 *General*

(1025) **Space exploration.** P. A. Moore. *National Book League, London* (1958). Annotated list of some 130 books.

(1026) **Spaceflight devices and instrument satellites.** *Luftfahrttechnik*, **4**, 288–90 (*Aug.*, 1958). (*In German.*) Report with list of papers of the IXth International Astronautical Congress, Amsterdam, 1958.

(1027) **Astronautics at Amsterdam.** I. *Aeroplane*, **95**, 389 (5 *Sept.*, 1958); II. *Aeroplane*, **95**, 411 (12 *Sept.*, 1958). Report of IXth International Astronautical Congress, Amsterdam, 1958.

(1028) **The Ninth International Astronautical Congress.** T. M. Tabanera. *Rev. Asoc. Argent. Interplanet.*, **6** (20/21), 8–13 (1958–9). (*In Spanish.*)

(1029) **The optimization problem for rocket vehicles subjected to medium and high accelerations: a literature survey.** B. Bergqvist. *Astronautik*, **1**, 101–17 (1959). (*In English.*) (133 *refs.*)

(1030) **A method of calculating the minimum launching weight of rocket vehicles subjected to medium accelerations.** B. Bergqvist. *Astronautik*, **1**, 96–100 (1959). (*In English.*) Derivation and application of a method for multi-step chemical rockets, subjected to 1–10 *g*. (4 *refs.*)

(1031) **IAF Congress 1958.** O. Klinker. *Astronautik*, **1**, 118–26 (1959). (*In Swedish.*)

(1032) **Spaceflight has begun.** K. Schütte. Kr. 16.50, 198 pp. *Hörsta Förlag, Stockholm* (1959). (*In Swedish.*) Trans. from the German.

(1033) **Participation in the CSAGI Rocket and Satellite Conference, Sept. 30–Oct. 5, 1957.** Vanguard staff. *Naval Res. Lab., Off. Tech. Serv. PB* 131960, 127 pp., $2.75 (*Jan.*, 1959).

(1034) **Stagnation-point shielding by melting and vaporization.** L. Roberts. *N.A.S.A. Rept.* 10, 55 pp. (*April*, 1959). (7 *refs.*)

(1035) **A mammoth gantry for Saturn.** *Missiles and Rockets*, **5** (24), 33 (8 *June*, 1959).

(1036) **Challenge of space.** W. von Braun. *Ordnance*, **43**, 901–5 (*May–June*, 1959).

(1037) **Probing interplanetary space.** S. W. Greenwood. *J. Roy. Aero. Soc.*, **64**, 299–301 (May, 1960).

(1038) **Nose cones: the case for ablation.** H. G. Lew, S. M. Scala and G. W. Sutton. *Missiles and Rockets*, **5** (24), 19–22 (8 *June*, 1959). Use of reinforced plastics; plasma jet development, ablation theories and their application to design.

(1039) **Nose cones: the case for heat sink.** J. D. Stewart. *Missiles and Rockets*, **5** (24), 16–18 (8 *June*, 1959). Designs are limited to relatively low values of the *ballistic parameter* (vehicle mass per unit frontal area/aerodynamic drag coefficient), and require considerable attention to manufacturing tolerances.

(1040) **General solution for optimization of staging of multi-staged boost vehicles.** C. H. Builder. *ARS J.*, **29**, 497–9 (*July*, 1959). The solution is applicable to a vehicle of any number of stages having different performances and characteristics, including stages with variable performance (*e.g.*, air-breathing-engine stages). Analytical procedures are outlined and an example of optimization of staging for min. cost is presented.

(1041) **Research in space.** *Science*, **130**, 195–202 (24 *July*, 1959). Review of work of NASA.

(1042) **Global aspects of the exploration of space.** H. L. Dryden. *Engr.*, **208**, 189–91 (4 *Sept.*, 1959). Paper read at Xth International Astronautical Congress, London, 1959; see *A.A.*, 1959–6, abs. 1046.

(1043) **Engineering for astronautics.** *Engng.*, **188**, 208 (11 *Sept.*, 1959). Review of some papers read at Commonwealth Spaceflight Symposium and Xth International Astronautical Conference, London, 1959.

(1044) **Escape and return.** *Engng.*, **188**, 154–5 (11 *Sept.*, 1959) Review of some papers read at Commonwealth Spaceflight Symposium and Xth International Astronautical Congress, London, 1959.

(1045) **Space research.** R. Fellows, J. E. Jackson, H. E. Newell and M. Stoller. *Engr.*, **208**, 405–8 (9 *Oct.*, 1959), 444–51 (16 *Oct.*, 1959). Paper read at AGARD meeting, Aachen, 24–5 Sept., 1959.

(1046) **The United States programme in space research.** H. E. Newell. *Proc. Roy. Soc. A*, **253**, 538–41 (29 *Dec.*, 1959). NASA programme in 1958.

.2 *Artificial Satellites*

[*See also* abstracts nos. 979, 992–7, 1000, 1004, 1005, 1017, 1102, 1122, 1123, 1127, 1128, 1133–1135.]

(1047) **On the behaviour, according to Newtonian theory, of a plumb line or pendulum attached to an artificial satellite.** J. L. Synge. *Proc. Roy. Irish Acad. A*, **60**, 1–6 (*Jan.*, 1958).

(1048) **The instrument equipment of the Earth satellite *Sputnik III*.** *Luftfahrttechnik*, **4**, 224 (*Aug.*, 1958). (*In German.*)

(1049) **Description of AFMDC prototype camera station for satellite surveillance.** W. E. Woehl and R. M. Waetjen. *Air Force Missile Devel. Center TR-59-3. ASTIA Document No.* 209327 (*March*, 1959).

(1050) **Atlas: concept for a manned space station.** *Spaceflight*, **2**, 66–8 (*July*, 1959). Project suggested by K. Ehricke (Convair-Astronautics)—space station with crew of 4 to be launched by Atlas missile into 400-mile orbit; maintained by 13–20 launchings/year.

(1051) **Projected manned satellite.** *Alata*, **15** (169), 52–60 (*July*, 1959). (*In Italian.*) Lockheed 4-man satellite.

(1052) **U.S. "space fence" on alert for Russian spy-satellites.** M. Mann. *Pop. Sci.*, **175** (1), 62–5, 198 (*July*, 1959).

(1053) **Earth satellites.** W. H. Stephens. *J. Roy. Aeronaut. Soc.*, **63**, 394–414 (*July*, 1959). Reviews satellites launched up to 12 Feb., 1959; also general discussion of orbital characteristics, launching and propulsion, navigation and control, possible scientific observations from satellites, and results obtained. (10 *refs.*)

(1054) **Temperature stabilization of highly reflecting spherical satellites.** G. Hass, L. F. Drummeter and M. Schach. *J. Optical Soc. Amer.*, **49**, 918–24 (*Sept.*, 1959). (10 *refs.*)

(1055) **Some general considerations of the heating of satellites.** A. J. Eggers, T. J. Wong and R. E. Slye. *J. Heat Transfer*, **81C**, 308–14 (*Nov.*, 1959). (12 *refs.*)

(1056) **Performance, control and guidance of satellite vehicles.** A. W. Lines. *Proc. Roy. Soc. A*, **253**, 500–11 (29 *Dec.*, 1959). Techniques for controlling satellite orientation and orbit within narrow limits, for space research purposes. Guidance problems associated with very eccentric orbits and lunar probes.

(1057) **Project Echo transmits telephone messages via satellite.** *Bell Labs. Record*, **38** (9), 334–7 (*Sept.*, 1960). Covers: *Echo I* satellite; new sensitive horn-shaped antenna used at Bell's Holmdel, N.J., laboratory to receive signals; advantages of passive satellites; importance of orbit altitude. A photo transmitted by radio *via Echo I* is reproduced *ibid.*, **38** (10), 396 (*Oct.*, 1960).

(1058) **Bell System to build and launch active [communications] satellite.** *Bell Labs. Record*, **38** (12), 450 (*Dec.*, 1960).

(1059) **Project OSCAR—something of the background.** B. Orr. *QST*, **45**, 55, 138 (*Feb.*, 1961). History of proposed amateur transmitter in orbit.

(1060) **Project OSCAR—something of the future.** D. L. Stoner. *QST*, **45**, 56–9, 140, 142, 144, 146 (*Feb.*, 1961). Orbital Satellite Carrying Amateur Radio is a proposal to send up a 2-m. amateur station with a future satellite. At least 10,000 amateurs in the U.S. are estimated to be active on 2-m. and it is proposed that the satellite station be used as a passive repeater. A phase-two station might contain an active repeater.

.3 *Lunar and Planetary Probes*

[*See also* abstract no. 978]

(1061) **Comparison of several propulsion systems for a Mars mission.** R. S. Kraemer and V. R. Larson. *A.S.M.E. Prepr.* 59–*AV*–46, 56 pp. (1959).

(1062) **Russia's Moon probe.** M. Allward. *Spaceflight*, **2**, 95–6 (*July*, 1959). Data on *Lunik I*, taken from Russian news reports.

(1063) **Explorer rocket research program.** G. Robillard. *ARS J.*, **29**, 492–6 (*July*, 1959). Design of the Jupiter-C missile; firing sequence; *Explorers I–VI* (payloads, orbits, history, scientific data obtained).

(1064) **Space research in relation to the Moon and the nearer planets.** T. Gold. *Proc. Roy. Soc. A*, **253**, 487–93 (29 *Dec.*, 1959). Possible researches in connection with plasma physics, Moon, Mars, Venus and Sun.

.4 *Spaceships*

[*See also* abstract no. 1015]

(1065) **Some radiator design criteria for space vehicles.** J. P. Callinan and W. P. Berggren. *J. Heat Transfer*, **81C**, 236–44 (*Aug.*, 1959).

.6 *Orbits*

(1066) **On the motion of a certain close [artificial Earth] satellite.** Y. Kozai. *Publications of the Astronomical Soc. of Japan*, **10**, 40–7 (1958).

(1067) **Effects of the Earth's oblateness on the orbit of an artificial satellite.** A. De Moraes. *Anais da Academia Brasileira de Ciéncias*, **30**, 465–510 (1958). (*In Portuguese.*)

(1068) **Determination of the orbit of an artificial satellite.** N. Carrara, P. F. Checcacci and L. Ronchi. *Ricerca Scientifica*, **28**, 1341–55 (*July*, 1958). (*In Italian.*)

(1069) **A modified Hansen lunar theory for artificial satellites.** P. Herget and P. Musen. *Astronom. J.*, 430–3 (*Nov.*, 1958).

(1070) **Development of some general theories of the orbits of artificial Earth satellites.** T. E. Sterne. *Astronom. J.*, **63**, 424–6 (*Nov.*, 1958).

(1071) **Solar activity and the braking of Earth satellites.** W. Priester. *Naturwissenschaften*, **46**, 197–8 (1959). (*In German.*

(1072) **Bibliography for satellite orbit computations.** Stanford Research Institute. *Air Force Missile Devel. Center TR*–59–22. *ASTIA Document No. AD* 215468 (*June*, 1959).

(1073) **Observations of the Russian Moon rocket *Lunik II*.** J. G. Davies, A. C. B. Lovell, P. Moore and H. P. Wilkins. *Nature*, **184**, 501–2 (15 *Aug.*, 1959).

(1074) **The continued progress of satellite 1958 δ_2 (*Sputnik III*).** B. R. May and D. E. Smith. *Nature*, **184**, 765–7 (12 *Sept.*, 1959). Progress since 31 Oct., 1958.

(1075) **Magnetic damping of rotation of satellite 1958 β 2.** R. H. Wilson. *Science*, **130**, 791–3 (25 *Sept.*, 1959). (7 *refs.*)

(1076) **New method of solution for unretarded satellite orbits.** J. P. Vinti. *J. Res. Nat. Bur. Stand.*, **63B** (2), 105–16 (*Oct.–Dec.*, 1959). (8 *refs.*)

(1077) **Dynamic problems associated with satellite orbit control.** B. W. Augenstein. *J. Engng. Industry*, **81B**, 281–8 (*Nov.*, 1959). (13 *refs.*)

(1078) **Lunar and solar perturbations on satellite orbits.** E. Upton, A. Bailie and P. Musen. *Science*, **130**, 1710–11 (18 *Dec.*, 1959).

(1079) **Analysis of the orbits of the Russian satellites.** D. G. King-Hele. *Proc. Roy. Soc. A*, **253**, 529–38 (29 *Dec.*, 1959). Results obtained at Royal Aircraft Establishment, Farnborough, in analysis of orbits of *Sputnik* 2 and *Sputnik* 3, especially concerning: (1) irregularities in air density in the upper atmosphere, (2) changes in the inclination of the orbit to the equator, (3) Earth's gravitational field. (12 *refs.*)

7—PROPULSION

.3 *Chemical Rockets*

GENERAL

[*See also* abstract no. 1061]

(1080) **Contour nozzle.** E. M. Landsbaum. *ARS Tech. Paper* 734–58, 22 pp. (1958). (18 *refs.*)

(1081) **Some fundamental considerations relating to advanced rocket propulsion systems.** J. Huth. *Rand Corp. Rept. P*–1479, 16 pp. (2 *Sept.*, 1958).

(1082) **Rocket propulsion.** W. B. Littler. *Nature*, **184**, 1264–7 (24 *Oct.*, 1959). Review of British Association papers.

·31 SOLID-PROPELLENT ROCKETS

(1083) **Recent advances in solid propellant grain design.** J. A. Vandenkerckhove. *ARS J.*, **29**, 483–91 (*July*, 1959). Types of grain (end-burning, side-burning, noncylindrical), internal ballistics, similarity rules, overall grain dimensions, fundamentals of grain design and use of design charts, mechanical behaviour of grains. (31 *refs.*)

·32 LIQUID-PROPELLENT ROCKETS

(1084) **Effect of fuel on screaming in 200-pound-thrust liquid-oxygen-fuel rocket engine.** I. Pass and A. O. Tischler. *N.A.C.A. Res. Memo. E*56 *C*10, 25 pp. (*June*, 1956).

(1085) **Effects of variations in combustion-chamber configuration on ignition delay in a 50-pound-thrust rocket.** D. J. Ladanyi. *N.A.C.A. Res. Memo. E*56 *F*22, 53 pp. (*Oct.*, 1956).

(1086) **Propellant vaporization as a criterion for rocket-engine design; calculations of chamber length to vaporize various propellants.** R. J. Priem. *N.A.C.A. Tech. Note* 3883, 36 pp. (*Sept.*, 1958).

(1087) **Evolution of the Spectre rocket.** *Aeroplane*, **95**, 705 (7 *Nov.*, 1958).

(1088) **Propellant vaporization as a criterion for rocket-engine design; experimental performance, vaporization, and heat-transfer rates with various propellant combinations.** B. J. Clark, M. Hersch and R. J. Priem. *N.A.S.A. Memo.* 12–29–58*E*, 16 pp. (*Jan.*, 1959).

(1089) **Analysis of flow-system starting dynamics of turbo-pump-fed liquid-propellant rocket.** R. P. Krebs and C. E. Hart. *N.A.S.A. Memo.* 4–21–59*E*, 45 pp. (*April*, 1959). (6 *refs.*)

(1090) **Power for space's Centaur.** R. Sanford. *United Aircraft Corps. Bee-Hive*, **34**, 2–4 (*Summer*, 1959). Pratt and Whitney XLR–115.

(1091) **Rocket turbines.** O. E. Lancaster and C. J. Bates. *J. Engng. Power*, **81A**, 280–9 (*July*, 1959). (12 *refs.*)

(1092) **Vaporization rate limited combustion in bipropellant rocket chambers.** E. Mayer. *ARS J.*, **29**, 505–13 (*July*, 1959). A one-dimensional model of the bipropellent rocket combustion chamber is analysed on the assumption that vaporization of liquid droplets is the rate-controlling step in combustion. The dependence of the gas flow variables on position co-ordinate in the chamber is determined in elementary analytic form subject to the assumptions that the vaporized propellents are instantaneously mixed and reacted in stoichiometric ratio and that droplet motion is governed by full entrainment in the product gas flow (*i.e.*, droplet velocity = local gas velocity). The formal solutions obtained permit comparison and contrast with monopropellent combustion. It is concluded that in the bipropellent system gas-velocity distribution is determined primarily by the droplet size spectrum and volatility of the more slowly vaporizing species and that the temp. distribution is strongly dependent on the droplet size spectrum and volatility of the more rapidly vaporizing species. Depression of the temp. levels associated with the presence of excess unreacted propellent gas near the injector implies the existence of flame-holding stability limits due to excessive mismatch in the local vaporization rates. Possible scope of applications and limitations of the combustion model are discussed. (16 *refs.*)

·33 PROPELLENTS

(1093) **Theoretical rocket performance of JP–4 fuel with mixtures of liquid ozone and fluorine.** V. N. Huff and S. Gordon. *N.A.C.A. Res. Memo. E*56 *K*14, 22 pp. (1957).

(1094) **Thermodynamic charts for the combustion products of nitric acid and kerosene.** W. H. Williams. *Aeronautical Res. Council Repts. and Memoranda R. & M.* 2982/*ARC* 16505, 8 pp. (1959). (7 *refs.*)

(1095) **Combustion temperature of liquid fuel rocket. Pt. I.** N. N. Sobolev, M. M. Belousov, G. M. Rodin, A. G. Sviridov, N. G. Skorobogatov and F. S. Faizullov. **Pt. 2.** N. N. Sobolev. V. F. Kitaeva, G. M. Rodin, F. S. Faizullov and A. I. Federov, *Zhur. Tekhn. Fiz.*, **29**, 27–36, 37-44 (*Jan.*, 1959). (*In Russian.*)

(1096) **Design problems with boron fuels.** E. M. Goodger. *Engng. Matls. Des.*, **2**, 380–1 (*July*, 1959).

(1097) **Estimation of performance of fuels with hydrogen peroxide oxidizer.** J. S. Gordon. *ARS J.*, 530–2 (*July*, 1959). Short empirical method for determining performance of (C, H, O, N) fuels with 90% H_2O_2, similar in approach to methods for other oxidants. Specific impulse and C^* results uncertain by 0·3%.

(1098) **The useful life of solid propellants at very high temperatures. Pt. 1.** M. Visnov. *ARS J.*, **29**, 500–5 (*July*, 1959). There are two successive zones of danger in the decomposition of propellents: (1) where the propellent function is faulty, (2) where it becomes a hazard to adjoining equipment. Use of cartridge-actuated devices (CADs) depends on location, temperature operation range, recycling, sealing, insulation protection, etc. Behaviour of nitrate-ester and composite propellents. Experimental programme at Frankford Arsenal, including apparatus for estimating useful life.

(1099) **Rocket propellents.** L. Crabs and J. Debaisieux. *Industries Chimique Belge*, **25**, 3–15 (1960). Review.

(1100) **Rocket propellents.** K. Yamazaki. *Yuki Gosei Kagaku Kyokaishi*, **18**, 241–51 (1960). Review.

.4 *Nuclear Rockets, Working Fluid*

(1101) **Relativistic treatment of an optimum rocket propulsion system under consideration of nuclear data.** T. Foelsche. *Air Force Missile Devel. Center TN–59–8. ASTIA Document No. AD* 214006 (*May*, 1959).

(1102) **Nuclear propulsion applied to satellite boosting.** W. A. Moser. *Mech. Engng.*, **81** (1), 38–40 (*July*, 1959). Condensed version of *A.S.M.E., Prepr.* No. 59–*AV*–24. (11 *refs.*)

.5 *Ion Rockets*

(1103) **Caesium-ion rocket research studies.** R. N. Edwards and G. Kuskevics. *A.S.M.E. Prepr.* 59–*AV*–32, 8 pp. (1959).

.6 *Miscellaneous*

(1104) **Plasma engine delivers nearly 2 lbs.** H. Gettings. *Missiles and Rockets*, **5** (24), 34–6 (8 *June*, 1959). Proposal of Republic Aviation Corp. (prototype has been operated for some months). Peak thrusts to be ~4000 lb. wt., average thrusts 1–2 lb. wt., specific impulse ~1700 lb. wt. sec./lb.

8—MISSILES

.1 *General*

(1105) **Britain's guided weapons.** *Aeroplane*, **95**, 328 (29 *Aug.*, 1958).

(1106) **Guided missile equipment and components.** *Aeroplane*, **95**, 425–6 (12 *Sept.*, 1958).

(1107) **Role of British territories in Atlantic Missile Range.** A. Everard. *Brit. Comm. Electron.*, **6**, 520–2 (*July*, 1959).

(1108) **Anti-overrun valve controls missile erection.** H. Jacobs. *Appl. Hydr. Pneum.*, **12**, 106–8 (*Sept.*, 1959).

.2 *Short-Range*

(1109) **Missile development at Valley.** *Aeroplane*, **95**, 588–590 (17 *Oct.*, 1958). Describes work at R.A.F. unit engaged on trials of Fireflash air-to-air weapon.

(1110) **Developing the Bloodhound.** *Aeroplane*, **95**, 653–6 (31 *Oct.*, 1958).

(1111) **Firestreak.** *Aeroplane*, **95**, 678 (7 *Nov.*, 1958).

(1112) **Military rockets could be simplified.** L. V. S. Blacker. *Engng.*, **188**, 351–2 (16 *Oct.*, 1959).

(1113) **Nike Hercules destroys Corporal missile in test.** *Bell Labs. Record*, **38** (7), 271 (*July*, 1960). Photos taken at White Sands.

(1114) **Nike Zeus Test Center at Kwajalein.** *Bell Labs. Record*, **38** (12), 468–9 (*Dec.*, 1960). Fifth test centre for the Nike-Zeus anti-missile missile (others are at White Sands, Ascension I., Point Mugu (Calif.), and the Whippany Laboratories). Notes on facilities and staff.

.3 *Ballistic*

(1115) **Thor.** *Aeroplane*, **95**, 537–8 (3 *Oct.*, 1958).

.4 *Upper Atmosphere Research*

(1116) **Atmospheric Knight-errant.** *Aeroplane*, **95**, 458–9 (19 *Sept.*, 1958). Description of Black Knight.

(1117) **Rocketry at the Needles.** *Aeroplane*, **95**, 554–5 (10 *Oct.*, 1958). The test facilities for Black Knight rockets described.

(1118) **Aerojet's new sounding rockets.** F. G. McGuire. *Missiles and Rockets*, **5** (25), 25–6 (15 *June*, 1959). Astrobee series.

.5 *Trajectories*

(1119) **Mathematical theory of the optimum trajectories of a rocket.** A. Miele. *Purdue Univ., School of Aeronaut. Engng., Rept. A–58–10* (*AFOSR–TR–58–154; ASTIA AD* 206361). 35 pp. (*Nov.*, 1958).

(1120) **A five-stage solid-fuel sounding-rocket system.** A. G. Swanson. *N.A.S.A. Memo.* 3–6–59*L*, 22 pp. (*March*, 1959).

.6 *Guidance and Control*

(1121) **The synthesis of optimum homing missile guidance systems with statistical inputs.** E. C. Stewart and G. L. Smith. *N.A.S.A. Memo.* 2–13–59*A*, 57 pp. (1959). (5 *refs.*)

9—RADIO AND ELECTRONICS; COMMUNICATIONS

[*See also* abstracts nos. 1057, 1058, 1059, 1060]

(1122) **Radio observations on the first Russian artificial Earth satellite.** *Trans. S. African Inst. Electr. Engrs.*, **48**, 363–9 (*Dec.*, 1957).

(1123) **The construction of a radio-interferometer for the localization of extra-terrestrial sources, and the registrations obtained in the case of the Sun and of artificial satellites.** A. H. G. Vieira and L. Q. Orsini. *Anais da Academia Brasileira de Ciências*, **30**, 299–306 (1958). (*In Portuguese.*)

(1124) **Studying tomorrow's communications . . . today.** H. D. Irvin. *Bell Labs. Record*, **36** (11), 398–402 (*Nov.*, 1958). Describes a machine (Sibyl) which works by intercepting the telephone lines of test users to give them simulated services in their normal environment, and automatically collecting data on the man-machine performance. See also abs. no. 1131.

(1125) **A comparison of long-duration secondary-power schemes for space vehicles.** A. P. Kelley. *A.S.M.E. Prepr.* 59–*AV*–39, 8 pp. (1959).

(1126) **Electro-optical instrumentation—automatic celestial tracking systems for terrestrial and space navigation.** A. L. Pogoda. Paper read at *Optical Soc. Amer.* 1959 *Spring Mtg.* (1959).

(1127) **On wave propagation in the atmosphere and satellite observation errors.** H. Knothe. *Air Force Missile Devel. Center TN–59–9. ASTIA Document No.* 215466 (*May*, 1959).

(1128) **Signals from satellite 1958 δ 2 (*Sputnik III*).** B. G. Pressey. *Nature*, **184**, 261 (25 *July*, 1959). Letter reporting confirmation of Munro's observation (*ibid.*, 1959, **183**, 1549) that pulse modulation of the satellite's radio signal was absent when it was not illuminated by the Sun.

(1129) **Power in space.** J. H. Fisher and W. R. Menetrey. *Mech. Engng.*, **81** (5), 49–51 (*Nov.*, 1959). Condensed version of ASME Paper No. 59–Av–18.

(1130) **Radio communication with a lunar probe.** W. T. Blackband. *Proc. Roy Soc. A*, **253**, 511–5 (29 *Dec.*, 1959). See also *J.B.I.S.*, 1959–60, **17**, 159–161. (2 *refs.*)

(1131) **Simulating speech through space.** *Bell Labs. Record*, **38** (8), 296–8 (*Aug.*, 1960). Bell Laboratories' Human Factor Engineering Group is using a simulation device ("Sibyl": see abstract no. 1124) to study the effect on long-distance telephone conversations of "abnormal" transmission delays likely to be experienced in using 'stationary' satellites, 22,300 miles up. Delays of 0·05–1·2 sec. being used.

(1132) **Communications in the space age.** [F. R. Kappel.] *Bell Labs. Record*, **38** (8), 313–4 (*Aug.*, 1960). Report of address by A. T. & T. President F. R. Kappel to University of California, on Project Echo and other aspects of space communications (including legal problems).

(1133) **Bell System proposes world communications network via outer space.** *Bell Labs. Record*, **38** (9), 351 (*Sept.*, 1960). Summary of testimony to U.S. Federal Communications Commission.

(1134) **DOPLOC tracking determines orbits of satellites.** L. G. DeBey. *Electron. Industr.*, **19** (10), 78–80 (*Oct.*, 1960). Doppler Phase Lock system.

(1135) **Balloon-borne telescope needs ultramin. preamps.** Electro Optical Systems, Inc. *Electron. Design*, **8** (22), 10–11 (26 *Oct.*, 1960). I.r. telescope for detection of unannounced satellites.

BOOK REVIEWS

An Introduction to Astrodynamics. By Robert M. L. Baker, Jnr. and Maud W. Makemson. 9 × 6 in. Pp. xiv + 358, with 47 fig. 1960. New York and London: Academic Press. (60s.)

For many decades astronomers have tended to congregate on the topmost floor of the ivory tower of science. The subjects of their study have been treated as essentially remote and a part from man, and in a sense astronomy has always been one of the most "pure" branches of science. But now a fundamental change is beginning to take place. As man's machines and later, man himself, leave the Earth and penetrate further into space, practical or applied astronomy must grow in scope and importance. One of the branches of astronomy to be very much affected by this fundamental change is that of celestial mechanics. For example, the problems of orbital prediction and determination have already become serious engineering problems. To describe this rapidly growing branch of astronomy, the word "astrodynamics" has been coined.

In the words of the authors of the book under review: "Astrodynamics is the engineering or practical application of celestial mechanics and other allied fields such as high-altitude aerodynamics; geophysics; and electromagnetic, optimization, observation, navigation and propulsion theory to the contemporary problems of space vehicles. It is not meant to include conventional aerodynamics or booster propulsion theory."

The book is the first to be published in this new field. It does not attempt to cover the whole general theory of what might be called "classical" celestial mechanics. Many books are available on the latter, some dating back to the last century. One due to be published shortly is by Samuel Herrick, to whom the present book is dedicated and who is Professor of the Department of Astronomy, University of California, where both Dr. Baker and Dr. Makemson lecture.

The book is partly based on a summer lecture course given by Dr. Baker. It is intended to serve as a text-book for such a college-level course, but also as a reference book for the engineer or other non-astronomer concerned with the relevant aspects of space technology. The reader is not expected to be already familiar with celestial mechanics or astronomy, although some mathematics and physics, including a good grasp of vector analysis and calculus, is essential.

To help the non-specialist, a glossary of over three hundred terms is included, and to help the student a number of exercises are offered for solution.

The twelve chapters are grouped into two general sections. The first section deals with fundamentals and background and includes discussions on the celestial mechanics of the minor planets and comets, geometry and co-ordinate systems and astrodynamic constants. The second section contains more detailed analyses and covers such subjects as orbit determination and improvement, the *N*-body problem, perturbations, non-gravitational effects, observation theory and applications to interplanetary orbits.

The text is lucidly written and adequately illustrated, and the printing and binding are up to the usual high standard of Academic Press. Although astrodynamics is a subject that must be expected to develop rapidly during the years ahead, this book will remain an invaluable introduction and reference source for a long time to come.

D. J. CASHMORE.

Vistas in Astronomy, Vol. 3. Edited by Arthur Beer. 10 × 7½ in. Pp. vii + 345, illustrated. 1960. London: Pergamon Press (120s.).

This third volume contains the research survey in astronomical topics begun by the previous two in the series. It seems certain, in fact, that the warm welcome accorded the first two, originally conceived as a tribute to Professor F. J. M. Stratton, has been such as to ensure the continuation of the series.

Again the international character of the series has been maintained and in the present volume are included reports of work being done in America and Europe, including Russia.

In Part I is found an article by the Astronomer Royal on the "Dynamics of Stars in the Solar Neighbourhood," a discussion by R. A. Lyttleton of "The Methods employed by Adams and Le Verrier in the Discovery of Neptune," three articles on "Applications of Relativity Theory," including the famous clock paradox, a discussion by G. M. Sisson (of Sir Howard Grubb Parsons & Co. Ltd.) of "The Problems involved in the Design and Construction of Large Telescopes," and other articles on the application of computers in astronomy, techniques in auroral investigations, the observation of the early Russian artificial satellites, and the observation and physics of comets.

Part II is more homogeneous in nature, being devoted to the stars in our galaxy and to cosmology. The subject-matter of the articles in this second part includes stellar astronomy, photometry, spectroscopy, evolution with reference to star formation and the galactic magnetic field and some observational aspects of cosmology.

The reader obtains not only a valuable survey of current research problems in astronomy, given by those best qualified to make such a survey, but also is left with an impression of the dynamic and healthy state of modern astronomy.

The book is attractively produced and is a worthy addition to Volumes I and II.

A. E. ROY.

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